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Manufacturing Value Modelling, Flexibility, and Sustainability: from theoretical definition to empirical validation

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Abstract

The aim of this PhD thesis is to investigate the relevance of flexibility and sustainability within the smart manufacturing environment and understand if they could be adopted as emerging competitive dimensions and help firms to take decisions and delivering value. Survey and case based researches are utilized with the aim of analysing global behaviour and understanding specific case studies. This combined research methodology aligns and compares macro-behaviour with micro-attitude. After the analysis of flexibility and sustainability relevance, we move on to analyse their application to physical supply chains, adopting a model-based research to conceptualise specific behaviours. We have assumed the use of model base research in order to analyse the evolution of strategies, due to the adoption of case studies, which are not longitudinal. Therefore, we use a mixed research methodology based on survey, case study and model. This mixed methodology is adopted with the scope of overcoming limitations of individual methods.

Flexibility: we start by investigating the topic of manufacturing flexibility to develop a framework, which allows companies to identify the impact of flexibility on their environment and processes.

Sustainability: we investigate what capabilities are needed for achieving competitive advantage in material efficiency, energy consumption, closed-loop control at industrial system level and competitiveness for improving sustainable performance. With this in mind, the adoption of the model based research for IS examines different strategies, creating a dynamic environment for agents, which can actively behave in the system and interact with each other.

The thesis is structured as following: Chapter 1 analyses the research background explaining assumptions, hypotheses and research questions, while Chapter 2 describes the research methodology adopted for this thesis. Chapter 3 presents results for each approach, and Chapter 4 provides discussions about them. Finally in Chapter 5 conclusions and future developments are discussed.

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1 Research background

1.1 Introduction and Background

In the current competitive scenario, manufacturing companies are facing various challenges related to an increasing level of variability. The variability means different sets of dimensions such as demand, volume, process, manufacturing technology, customer behaviour and supplier attitude, transform the industrial systems engineering domain. This trend is now accelerating, causing a direct impact on the value chain and related physical supply chains as well as factory design and management [1]. This new paradigm is known as “the fourth industrial revolution” or “Industry 4.0”. The term “Industry 4.0” refers to a new production patterns, including new technologies, productive factors and labour organizations, which are completely changing the production processes and the relationship between customer and company with relevant effects on the supply and value chains [2]. Even though most of the aforementioned innovations are in an embryonic stage, they are still an important part of research and progress. The association of these cause new “matched technologies” which could work in a physical and digital environment.

These changes in business models, production paradigm and logistic operations are driving various production sectors and replacing the traditional industrial systems, bringing in the fourth industrial revolution [3].

The state of uncertainty in the application of these paradigms creates a complexity in the understanding of the effects of such systems. For this reason the collaboration and integration between different global stakeholders (governments, universities, companies, society) are mandatory in order to improve understanding of the emerging dynamics.

Several national strategies and new technological roadmaps (e.g. the German high tech strategy “Industrie 4.0” or the Italian cluster “Fabbrica Intelligente” (FI)) aim at approaching this transformation enhancing the sustainability, flexibility and re-configurability of current manufacturing systems among many other competitive dimensions. New emerging technologies could allow the next generation of manufacturing systems to become real smart factories [4].

As well as the two aforementioned strategies (Industrie 4.0 and FI), companies are applying innovative solutions, including the “Internet of Things” (IoT), cloud computing, miniaturization and 3D printing that will enable flexible and sustainable industrial processes and intelligent manufacturing.

Shown below are ten road maps, which have been addressed (Table 1).

Table 1 ten road-mapping programs

Country	Title	Date of issue
Austria	BMVIT (Austrian Ministry for Transport, Innovation and Technology) Innovation: Solutions for the future	October 2009
Denmark	Manufacturing 2025: Five future scenarios for Danish manufacturing companies	May 2010
Finland	Finland’s regional development strategy 2020	September 2010
France	France Europe 2020: A strategic agenda for research, technology transfer and innovation	February 2013

Ireland	Making it in Ireland: Manufacturing 2020	2012
Latvia	Sustainable Development Strategy of Latvia until 2030	June 2010
Netherlands	Smart Industry – Dutch industry fit for the future	April 2014
Sweden	Swedish Production Research 2020	2008
UK	The future of manufacturing: a new era of opportunity and challenges for the UK	2013

Industry 4.0 has the potential to improve productivity and competitiveness, increase energy and resource efficiency and effectiveness and therefore protect the environment. It could enable the transition to a circular or a closed loop economy in which end of life products are reused, remanufactured and recycled. All in all, these developments would lead to the emergence of more sustainable production and consumption pattern, and could provide opportunities for developed and developing countries to achieve economic and sustainable growth.

The majority of the aforementioned roadmaps are mainly focused on specific topics [5]–[7] (Table 2): i) Flexible, personalized and innovative production systems, ii) Strategies, methods and tools for industrial sustainability, and iii) Digital transformation in the manufacturing environment.

The first research priority (Flexible, personalized and innovative production systems) has as its major theme "Customization", which over the past 15 years has emerged as one of the strategies that allows companies to supply bespoke products that can be mass-produced in a flexible manufacturing systems.

These topics are associated with different aspects of product development, such as Information and Communication Technology (ICT) solutions for the acquisition of the client's requirements, product configurators, advanced measuring systems, platforms for client monitoring and technologies for personalized production, such as additive manufacturing, micro-manufacturing, hybrid processes, etc. Furthermore, there is a need for new flexible supply chain model that considers product modularization strategies, postponement and "multi decoupling points' with a view to bespoke production. High production efficiency is also an essential condition for the competitiveness of all businesses, especially those working in sectors with high volumes and reduced margins. Manufacturing companies need to achieve a substantial improvement in performance to stand out from low-cost countries by manufacturing high-quality products in an extremely flexible system that make it possible to maintain their efficiency even when demand varies dramatically. Thanks to a global optimization of the entire energy system a reduction in waste and energy consumption can be achieved.

The second topic focuses on "strategies, methods and tools for industrial sustainability", which has become a key issue on the agendas of industrialists and politicians [8]. The aim is for an improved understanding in environmental, social and economic challenges leading to a transformation in industrial behaviour. Three waves of change will shape the industrial system over the next two decades, these are: i) improvements in environmental performance without changing current products and processes, ii) development and introduction of new technologies, and iii) changes in the industrial system as a whole. This requires awareness and reengineering of the industrial processes in order to reduce carbon emissions and improve energy efficiency shifting towards the Industrial symbiosis. Industrial symbiosis is, therefore, a system in which all activities, starting from extraction and production, are organized in such a way that waste becomes a resource, unlike the linear economy, in which, a product becomes waste when consumption ends, forcing the economic chain to continually repeat the same sequence: extraction, production, consumption, disposal. These systems must be coherent with the evolution of the markets and future technologies, using them as a competitive lever towards the three areas of sustainability (economic, environmental and social). Within industrial sustainability, specific interest in de-manufacturing has recently grown due to the rising cost of raw materials and specific laws introduced by the EU to improve the recovery rates of the materials. Furthermore, the demand for materials critical to the manufacture of high-tech products is constantly increasing in Europe, causing huge problems in economic and strategic terms (e.g. electronic waste, which is an important source of metals for technological products).

The third and final research priority concerns the “Digital transformation of manufacturing environment”; companies are weighed down with old production facilities, which reduce flexibility. However, companies have now understood the relevance of implementing new technologies in order to face these issues. Digital manufacturing (DM) allows the simulation of the whole supply chain with the idea of the virtual factory, integrating procurement, production, product logistics, service and diverse IT technologies in order to predict, solve and control problems in the virtual and physical environment. DM technologies allow: i) the reduction of time to market, ii) decrease in costs and iii) and the increase of process flexibility by analysing production data.

Table 2 Research priorities emerged by roadmaps and innovative programs

Research priority	**Description**
Flexible, personalized and innovative production systems	Need for new flexible and agile supply chain models that consider product modularization strategies, postponement and “multi decoupling points’ with a view to customize production.
Strategies, methods and tools for industrial sustainability	The aim is for a better understanding of how to respond to environmental, social and economic challenges and therefore transform industrial behaviour. Three waves of change will shape the industrial system over the next two decades, these are: i) improving environmental performance without changing current products and processes, ii) developing and introducing new technologies, and iii) changing the industrial system as a whole.
Digital transformation in the manufacturing environment	Companies have understood the relevance of implementing new technologies in order to face these issues. Digital manufacturing (DM) embraces the integration between the digital and physical environment, including the application of modelling and simulation techniques, visualization, data analytics, manufacturing, supply chain and various other processes in order to manage the overall product life cycle.

It is fundamental to have a universal vision of the current scenario in order to design a future for the community, which reflects common objectives and values.

This universal vision should explain how technologies are not only changing manufacturing but also the entire world and how they are re-designing the economical, social and environmental scenario in which we live.

1.2 Digital transformation: the fourth industrial revolution

The term “revolution” describes a radical and unexpected changing. During the past, revolutions took place when technologies were directed towards economical and social events, which have transformed the world.

Furthermore, the term “Industrial Revolution” has caused a lively discussion about its beginnings and applicability over recent times in the scientific community (Coleman, 1983). However, it has been widely accepted as a key element in the growth and development of technology, changing the condition of human society and the environment. It can be argued that the industrial revolution is a set of macro inventions allowing an acceleration of micro inventions. This creates events that irreversibly change the face of society in a global sense (Table 3).

Table 3 Industrial revolutions

Industrial revolution	Time periods	Technologies and capabilities
First	1760-1840	Water- and steam-powered mechanical manufacturing
Second	Late 19th century -1970s	Electric-powered mass production based on the division of labour (assembly line)
Third	1970s-Today	Electronics and information technology drives new levels of automation of complex tasks
Fourth	Today-	Sensor technology, interconnectivity and data analysis allow mass customisation, integration of value chains and greater efficiency

The first industrial revolution between 1760 and 1840, introduced mechanical production supported by the development of the railway and the invention of the steam engine.

The second industrial revolution starting at the end of the nineteenth century and finishing at the beginning of the twenty-century, allowed mass production through electricity and the introduction of the assembly line.

The third industrial revolution starting in the 1970s is often named the “digital revolution” because it developed through semiconductors, mainframe computers, personal computers and the diffusion of Internet.

Today we are witnessing the beginning of the fourth industrial revolution, which is the result of the digital revolution. It is characterized by a widespread application of the Internet, which has become easier to use, and the application of intelligent components, robots and technologies.

This revolution supports the creation of the “smart factory” in which physical, digital and flexible production systems are integrated with the aim of reaching “mass personalization” and “faster product development”.

At this point, it is fundamental to underline that Industry 4.0 is not only the application of digital components and technologies in the manufacturing sector but it is also extended to medicine, chemistry, physics and nanotechnologies. Industry 4.0 is the integration and interaction of these technologies towards physical and digital domains, which will make it stand out from the other industrial revolutions.

Manufacturing has switched from mass production to mass customization [9]. No longer is it based on scale and volume effects but on flexible and localized production situated close to customers. It manufactures "on demand" and no longer creates inventory, adapting itself to needs. It is more predictive and auto-corrective and it involves less trial and error. Its logic is now focused not on the product but on usage, and it has also switched from a rigid form of labour, inherited from Taylorism, to a flexible form, enhancing the appeal of work as a result [10]. This potentially represents a complete overhaul of the economic rational behind business.

1.2.1 Trends in the smart manufacturing environment

The fourth revolution is shaping scenarios of global change and development that have an impact on the lives of people, companies and communities, influencing the economy and consumption. Numerous studies have identified and analysed these megatrends of change and development.

A study has been conducted to find information from various research articles and interviews with Siemens experts in order to investigate and identify the main trends, which drive the new era of manufacturing:

- Supply chain complexity;
- Mass customization;
- Demographic Change;
- Industrial Sustainability;
- Technological Innovation;
- Globalization;
- Regulatory constrains.

1.2.1.1 Supply Chain Complexity

Supply chain complexity can be defined as the level of detail and dynamic complexity exhibited by the products, processes and relationships that make up a supply chain. Three drivers stand out in terms of their impact on plant performance: i) lengthy supplier lead times; ii) instability in the master production schedule; iii) variability in demand.

Furthermore this complexity even increases when considering the customization as well as the digitalization and the resulting interconnectivity between the product and business processes [11].

1.2.1.2 Mass customization

Mass customization relates to the ability to provide bespoke products or services through flexible processes in high volumes and at reasonably low costs. It has been identified as a competitive strategy by an increasing number of companies. Agility and quick responsiveness to changes have become mandatory to most companies in view of current levels of market globalization, rapid technological innovations, and intense competition.

Mass customization broadly encompasses the ability to provide individually designed products and services to customers in the mass-market economy.

1.2.1.3 Demographic Change

Over the next decades, it is estimated that the global population will grow by 18%, reaching a total of 8.4 billion people by 2040.

One consequence of these changes will be an increase in the percentage of senior workers. It will therefore be necessary to find a balance between the need to allow over-65s to prolong their working life and the need to create new job opportunities for the young. Moreover, this also meets the broader need to increase the wellbeing of all workers in terms of increased satisfaction, safety and inclusivity (Cluster Fabbrica Intelligente).

1.2.1.4 Industrial Sustainability

According to the traditional industrial view, product design and process technology typically determine the types of pollutants emitted, solid and hazardous wastes generated, resources harvested and energy consumed.

Unfortunately, in a business environment of resource and energy supply uncertainty, the traditional view and the related business model, requires the continuous exploitation of new markets for growth, the enhancement of products to maintain demand and global sourcing to sustain margins, whilst absorbing the costs of compliance with end of life cycle legislation, is clearly unsustainable.

It is generally agreed that sustainability has environmental, social and economic dimensions [12].

1.2.1.5 Technological Innovation

Technological innovation has historically been considered the main effective source of competitive advantage among enterprises and the economic growth and social benefit of countries. Innovation has the ability to not only increase productivity but also creates processes for new types of products.

Innovation can also provide the means for manufacturing flexibility [13].

1.2.1.6 Globalization

The trend in globalization has changed the ways of connecting customers with products and therefore the factors that are analysed, be it the company, the manufacturing network, or the supply chain.

Because of globalization, the vast majority of manufacturing in large companies is carried out in value networks. As globalization of markets raise competitive pressures, one essential requirement for the survival of organizations is their ability to meet competition. Market needs cause unlimited changes in the life cycle, shape, quality, and price of products [14].

1.2.1.7 Regulatory constrains

From a regulatory point of view quality refers to the basic objective requirements under the existing laws to assure that goods/food are safe, not contaminated or adulterated or fraudulently represented.

Food quality and safety requirements are neither optional nor negotiable [15].

The described megatrends characterize and influence the global scenario of competition for the manufacturing sector. The specific challenges posed by megatrends must be dealt with by implementing industrial strategies that follow the development of appropriate strategic actions.

1.2.2 Industry 4.0 technologies

In this section, the core technologies of Industry 4.0 are described. The key representative technologies are:

1. *Cyber Physical Production Systems (CPPS):* is a basic technology for building a smart factory, and it is being studied alongside methods such as:
   a) *Plug and produce*: this is a collection of stations or modules for assembling or checking parts. In case of breakdown modules can be replaced with others having similar functions and interfaces or be adapted to new processes. Modules can also be added to increase production volumes [16]. The concept follows a product-centric approach, where the product governs its own production, there is no need for central coordination. Production systems are composed of intelligent modules that are able to configure themselves, execute a defined set of skills autonomously and/or incorporate with others [17]. A production unit is aware of its production skills, capabilities, state, and its physical and virtual environment. Different production units can be identified such as machines, robots or conveyors.
   b) *Smart products:* these are products that are capable of doing computations, storing data, communicating and interacting with their environment. To this end, it is necessary to develop chips and microprocessors as well as embedded systems [18].
2. *Industrial Internet of Things (IIoT):* this is the industrial version of the Internet of Things. It is a systematic expansion of automation and a progressive improvement in machine communication. IIoT mainly relates to human-object interaction. This helps users to track a sequence of events and activities as and when they occur [19].
3. *Cloud manufacturing (CM):* this is the cloud computing technology applied in the manufacturing area. In this context, manufacturing resources and capabilities are virtualized and coordinated in a cluster, as a result, all components within the CM can perform in real-time and in collaborative manufacturing task [20].
4. *Data Analytics (DA):* The increasing volume of data, generated by CPPS and IIoT, needs to be stored and processed and analysed in real-time. Big data has emerged as a tool, which is able to provide data analysis, knowledge extraction, and advanced decision-making [21].
5. *Augmented and virtual reality (AR/VR):* Augmented-reality-based systems can support a variety of services, such as selecting parts in a warehouse and sending repair instructions over mobile devices. VR applications have been well received in virtual prototyping, web-based virtual machining, assembly, fault diagnosis and learning, and various types of manufacturing operations [22].
6. *Additive Manufacturing (AM):* the implementation of AM for technical prototyping, pre-production series and short series production can bring benefits in terms of cost reduction and shortening of the time-to-market in product development [23].
7. *Simulation techniques-Digital twin (ST):* simulation techniques such as the discrete event simulation (DES) of a manufacturing plant i) allow the study of factory production and ii) avoid problems of robustness of adopted meta-models with

proper methodologies [24]. In this context the Digital Twin is arranged as a virtual model of process, product or service. This pairing of the virtual and physical worlds allows analysis of data and monitoring of the whole system. From a simulation point of view the Digital Twin approach is the next wave in modelling and optimizing technology [25].

1.2.3 Impact of Industry 4.0

The impact and the relevance of the fourth industrial revolution will give rise to economical, social and cultural changes. These effects are impossible to predict. This section aims to analyse and describe the potential impact of Industry 4.0 on industrial systems, economy, governments and society.

1.2.3.1 Impact on Industrial systems

Today's industry is faced with an increasing demand for adaptable production systems. For instance, for a quick response to market demands, production systems need to be extended or downsized dynamically without shutdown. Production systems must rapidly adapt to produce new products or product variants. With current automation technology, such changes usually come at the cost of engineering and re-programming, paired with business loss due to production system downtimes [26].

More flexible machinery and technology concepts such as CPPSs, AM procedures and ICT technologies are making their mark in the industry 4.0 context.

Several studies agree that CPPS represents the core technology towards the fourth industrial revolution but at the same time underline that the introduction of such technologies could cause distress in value and supply chains [27]. In fact, cost savings of up to 60% - 70% are expected for the planning and engineering phases of products and their production systems, and 10% - 20% for the actual production. Productivity improvement is expected to be in a range of 15% - 20% (Table 4). However, none of the studies provide convincing arguments that the predicted cost savings can actually be achieved, and they also do not outline concrete CPPS systems.

Table 4 Potential savings derived by the application of CPPS system

Costs and Effects	Savings Potential
Manufacturing Costs	-10% to – 20%
Downtime	Given by reconfiguration and planning potentials
Personnel Reconfiguration	-20% to -30%
Planning	-60% to -70%
Asset Reconfiguration	No savings

AM procedures have developed from a cost-intensive technology to a rapid production technique for a wide number of products with the most varied of materials. One of the greatest advantages of AM is the virtually complete freedom in the product development design. To make use of these opportunities new knowledge, abilities and skills are required. For direct digital production, the majority of the production and process parameters must already be defined and laid down in the product development phase. The only limits are the external dimensions. AM can often reduce costs thanks to its lower consumption of materials [28].

Finally, as the ICT technologies begin to penetrate the company processes, the technological innovation cycles of the manufacturing industry will also begin to change. The shortening of the product cycles also entails a continual adjustment of production capacities: new materials have to be assessed for their own added value and processed. New technologies and features have to be integrated into solutions, and the facilities necessary for this have to be developed.

It may be that completely new production systems have to be planned and built for each new product generation. In order to achieve the goal of efficient supply with the best possible returns, the company's own value added network has to be expanded and developed and continually followed.

1.2.3.2 Impact on Economy

The industry 4.0 impact on the economy is difficult to predict due to its size. Obviously, these changes will affect all the main economic variables: consumption, employment, growth and GDP, investment and inflation. In this section we focus on the effects of economic growth and employment [29].

Economic growth is a topic, which divides economists. On the one hand "pessimists" claim that the benefits resulting from the application of such technologies will be irrelevant due to the high advantages achieved previously. On the other hand, "optimists" argue that these technologies and innovations will bring an increase in productivity and therefore economic growth. We think that the impact of Industry 4.0 will have a positive influence on economy due to these three reasons:

1. It satisfies a billion people's needs in a global economic environment;
2. It reduces negative externalities such as the carbon footprint;
3. It creates a new business model, new organization management model and new economic system.

Regarding employment, it is important to underline that the sound effects on economic growth won't necessarily have a positive influence on employment at least in the short period. New technologies will drastically transform the labour market resulting in many working activities being automated, and therefore creating less employment than the previous industrial revolutions [30]. In view of this, we have to highlight that in the future new jobs will arise in consequence of demographic, geopolitical and cultural changes. Finally, job markets will seek "worker flexibility" due to the rapid technological changes instead of a specific education.

1.2.3.3 Impacts on governments and society

Systemic changes are characterised by the interplay between technological and social shifts. These shifts are coming together and enabling a comprehensive, embedded process of change. This holistic approach also requires a broader understanding of innovation policy. Along with this come questions about research funding and transfer from academia into business. Also social acceptance of new technologies involves the promotion of a modern personnel policy, the efficiency of Research & Development (R&D) systems and the establishment of new business models. This requires more coordination across ministries and policy makers. Just as in economical matters, speed is of the essence here. However, it should not be everyone scrambling at the same time, but rather a coordinated, concerted effort that follows a strategy with the aim being the broadest possible social diffusion of digitalization [29].

1.3 Important literature items for this work

In consequence of the aforementioned description of the smart manufacturing environment, we will focus now on the specific literature providing i) the theoretical framework for this research and ii) the definition of key terms and topics related to our study. We start from an explorative study based on qualitative reviews on value creation and modelling in order to specify the value concept within manufacturing companies and prepare the field for the competitive dimension concept. Then we will move to digitalization including flexibility and reconfiguration of manufacturing systems. Finally we will focus on the sustainable supply chain and related topics as well as performance management and influencing factors. We will use this data to analyse the current situation and reinforce our case studies.

Literature reviews for each topic are provided by selecting papers through a computer search from four databases: ScienceDirect, Scopus, Emerald and Web of Science. Authors chose these databases for their ample covering of articles in the field. They offer search combinations using “and” and the possibility to search for keywords.

The qualitative literature review process was composed of two parts [31]: firstly, an explorative and unstructured part that had a number of different origins; and secondly, a more structured review process involving searching databases using search strings and dashboards.

1.3.1 Manufacturing firms value modelling and mapping

Authors’ strategy was to identify articles that included “Value creation”, “Value modelling”, “Process Improvement”, or “Business Model” as keywords in all fields. Additionally, Authors took into account various synonyms of each of these terms.

Our search identified 104 empirical academic papers that were published between 2000 and 2017. Their titles, abstracts and texts were reviewed in detail for relevance to the study.

The distribution of publications over the years (Figure 1) shows a growing trend of articles and it reveals a significant increase from 2013, this could be due to the implementation of “Industry 4.0”.

In terms of geographical distribution, the publications reviewed where from many different countries around the world, based on the main author's university affiliation. A few countries stand out: The UK, The USA, and Italy. Hence, it might be argued that value creation is primarily rooted in these countries.

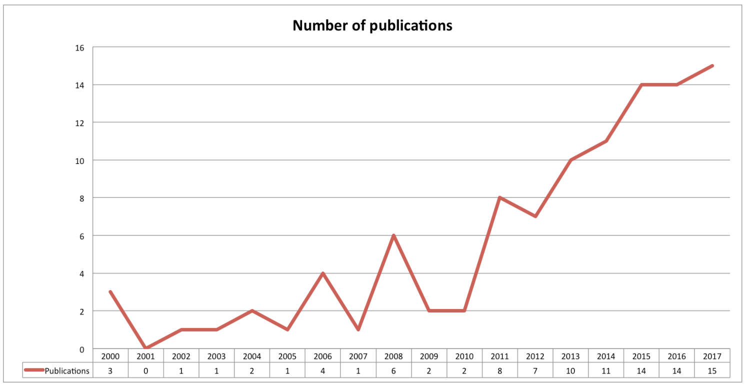

Figure 1 Distribution of publication over years

Based on the findings of this review, it is possible to establish an overview of the predominant value strategy characteristics. For [32] the ability to create value for a company is based on the capacity to develop strategies that respond to market opportunities but the Author also underlines the complexity "to understand the key internal resources and drivers of performance".
[33] draws our attention to the need "of flexible and adaptable platforms which enable technology and internal integration between ERP and MES levels of manufacturing industry". This concept has also been analysed by [34], who agrees that there is a need for "tools to discuss what the project itself and the base organization should do to enhance this value creation".

Like [35] explains in his work, business process has a relevant role in the value creation, since it "describes how something is done in an organization" and it is defined "as end-to-end work which delivers value to customers".

Finally the Authors highlight the importance of the Industry 4.0 project. This addresses the changes made by the merging of modern information and software technologies with classic industrial processes and the values brought about by this transformation. It is, however, reasonable to suspect that broad penetration of these technologies in industry will take a considerable amount of time and this should be taken into consideration when planning the corresponding investments.

1.3.2 Digitalization of manufacturing systems

A methodology based on a qualitative literature review has been adopted in order to understand from the scientific point of view, what the level of digitalization in the Manufacturing Execution System (or Manufacturing Operations Management) is.

The aim is to investigate and define the state of the art technologies adopted by manufacturing company at MES/MOM level. The authors' strategy was to identify articles that included "manufacturing flexibility", "manufacturing execution system", "manufacturing operations management", "smart factory" and "industry 4.0" as keywords in the paper. The search identified 52 empirical academic papers that were published between 2000 and 2017. Their titles and abstracts were reviewed in detail for relevance to the study. These papers provided a summary of the most recent state of digitalization in MES/MOM. The earliest paper included in the dataset was published in 2002 and the most recent in 2017. The distribution of publications over the years (Figure 2) shows that in 2006 a peak was reached followed by a decrease in interest until 2014. After 2014 when "Industrie 4.0" was introduced, the amount of publications increased again and over the last three years has reached new heights (2015, 2016 and 2017).

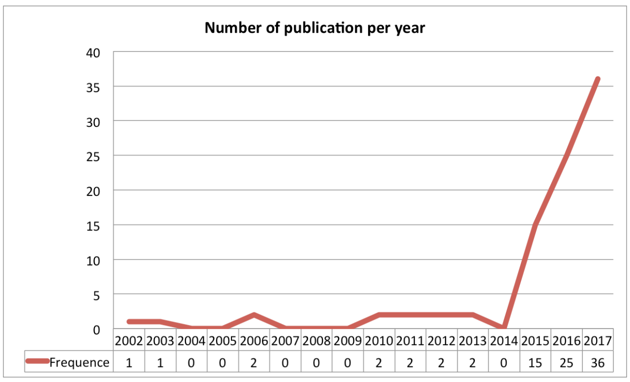

Figure 2 Distribution of publication over years

In terms of geographical distribution, the publications originate from many different countries around the world, based on the main author's university affiliation. One country stands out: Germany. Hence, it might be argued that this topic is primarily rooted in this country.

What emerges from the literature review is an overview of the current technologies applied to MES/MOM, in particular Brettel et al., highlight the essential role of additive manufacturing which is considered a keystone of Industry 4.0, and in combination with iterative development processes, allows manufacturing flexibility both as reactive and proactive manufacturing strategies [36]. However, Hänel et al. pay specific attention to the role of data analytics as a key technology of Industry 4.0, with a specific focus on the integration and analysis of production data. It is also emphasized that this data integration includes multidimensional views on flexibility [37].

Diverse authors promote the concept of CPPS, in Michniewicz's work, for example, the focus is on industrial robots which have great flexibility due to their kinematical degrees of freedom and the versatility of manageable tools, sensors and other peripheral devices. The Plug&Produce approach was introduced in order to facilitate the reconfiguration of robot cells. The robot cell components and the smart product to be manufactured are defined as CPPS, which store data, process data intelligently, interact and communicate with each other [38]. Also Scheifele et al., identify CPPS as a core technology for smart factories, "the use of CPPS provides added value for smart factories like optimized production of customized products and resource-efficient production". Furthermore, they pinpoint the self-reconfiguration concept, in which the production will organize itself, where each part "knows" its requirements and each machine "knows" its capabilities [39].

Other technologies linked to the CPPS are IIoT and CM. In recent times, these can connect materials, sensors, machines, products, supply chain, and customers, and exchange information and control actions with each other independently and autonomously [40].

However, CM provides a shared environment for manufacturing, computing, knowledge and resources. It creates an environment where computing and service resources in the cyber world are connected to the machines and robots in the physical world, thus forming a cyber-physical system [41]. For Wieland et al., a smart factory is defined as a factory that is "context-aware" and assists people and machines in executing their tasks. Focus is established to improve failure management by coordinating and supporting the repair process with "context-aware" workflows [42]. The repair process and in particular the maintenance management is also covered by VR/AR. Turner et al., claim that a fundamental aspect of the smart factory is virtual manufacturing, whereby the process of manufacturing is simulated from product design to final production and each stage is explored in a VR setting [43].

In conclusion, on analysing these results, we can say that over the last two years digitalization at the MES/MOM level has started to be studied more thoroughly and the most valid technologies are CPPS, Data analytics, CM, IIoT, AM, VR/AR and simulation techniques.

1.3.3 Manufacturing flexibility

The authors' keywords to identify relevant papers were "manufacturing flexibility", "flexibility type", "flexibility model" and "influence factor". This resulted in 146 empirical academic papers published between 2000 and 2017. The distribution of publications over these years show that there were various troughs and peaks. After 2013 when "Industrie 4.0" become more widespread, the amount of publications increases again (Figure 3). The distribution of publications shows that the top five keywords are "flexibility", "manufacturing", "empirical research", "manufacturing systems" and "flexible manufacturing systems".

Another important finding in the literature review is that a high percentage of publications make reference to the flexibility model presented by Browne et al and Sethi and Sethi which differentiates between basic, system and aggregated flexibility.

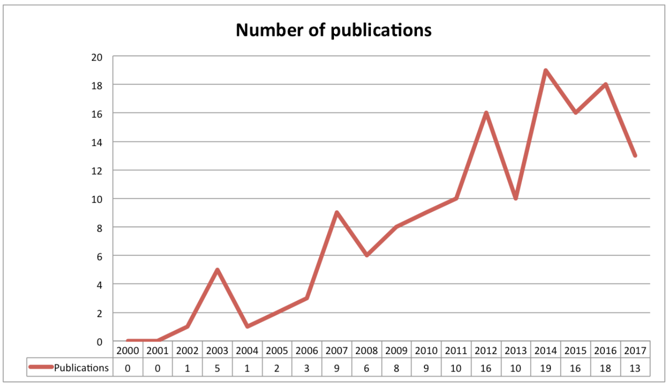

Figure 3 Distribution of publication over years

To reach more dynamic capabilities, companies need more flexibility in operations that will create a positive value and gain competitive advantage for the firm [44].

To address fluctuations in demand, the firm must maintain flexibility of manufacturing system through simulation and other scientific operations techniques [45].

Flexibility of manufacturing systems can be defined in various groups such as processes, equipment, products and production volumes [46].

In their work Sethi & Sethi present a hierarchical model consisting of eleven types of flexibility, which are either affecting the important components of the system and the product (machine, material handling, operations) or the system as a whole [47]. Even though the aggregated flexibility already hints at different triggers for the flexibility demand, there are other authors that have a stronger focus on the causes for flexibility.

Kara and Kayis for instance investigate the origin of flexibility demand and state that it can either occur externally from a market point of view or internally from a manufacturing process point of view. Furthermore they create a mapping between the causes of flexibility demand and flexibility types [48].

We can identify three main types of paradigm: dedicated manufacturing lines (DML), flexible manufacturing systems (FMS), and reconfigurable manufacturing systems (RMS).

On reviewing past papers it becomes clear that there are few studies involving "flexibility + sustainability" in combination. Sustainability and flexibility need to be developed in order to face the challenges of globalization and climate change.

The aim of every organization in world should be minimize energy consumption and maximize resources with the objectives of "cleaner production" and improved environmental sustainability [49].

Hence, it may be understood that combining flexibility and sustainability is a complex operation. Next, we will analyze sustainability issues and points.

1.3.4 Sustainable supply chain management

In order to explain, comprehend and implement industrial sustainability, it is mandatory to understand how to apply sustainability to the supply chains. Industrial sustainability has attracted much interest in the last few years (Figure 4), and for this reason various definitions can be found in the literature [50].

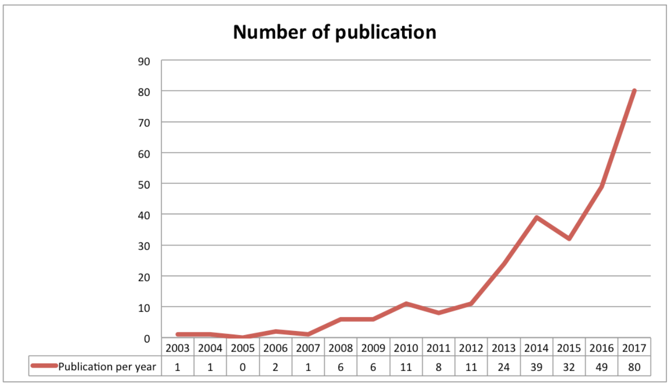

Figure 4 Distribution of publication over years

Seuring, who is considered one of the most relevant researchers in this field, presented a description of this concept. He claims that sustainability is “a multi-dimensional and multi-scale term”, which includes topics related to the “Triple Bottom Line” that balance the environment, the economy and society, underlining how it is also a multi-scale objective considering temporal, geographical and institutional scales [51].

In addition, sustainable supply chains (SSC) have been recognized as a key for sustainable development and an added value for achieving improvements at the production level. SSCs are defined as the management of all components of a system, including tangible and intangible resources (such as materials, information and capital flows), and take into account all three dimensions of sustainable development [52], [53]. Furthermore, Pagell and Wu, define sustainable supply chains as specific activities, which develop each chain [54].

Finally, Bardurdeen proposes a more precise definition of sustainable supply chains as the management and integration of all operations that take place during the product life cycle allowing the sharing of information between these stages and companies taking into consideration all the three dimension of the triple bottom line [55].

1.3.5 Value mapping framework for sustainable manufacturing

The authors consulted the database searching for “Value Mapping”, “Industrial Sustainability”, and “Manufacturing”, in papers published between 2000 and 2017. This resulted in 125 papers that form the base of further analysis. The earliest paper included in the dataset was published in 2002 and the most recent in 2017 (Figure 5).

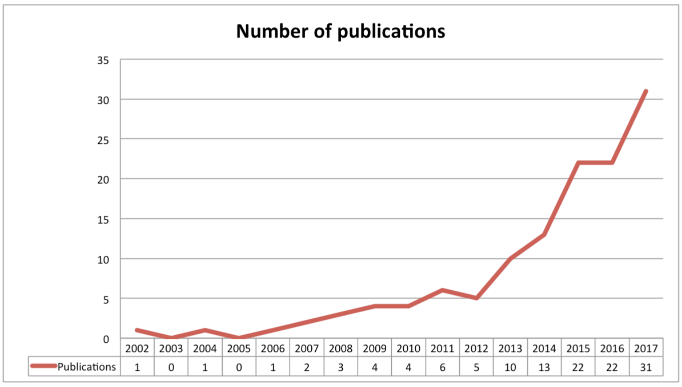

Figure 5 Distribution of publication over years

The papers were published in six research journals: Journal of Cleaner Production, IFIP Advances in Information and Communication Technology, International Journal of Operations and Production Management, International Journal of Advanced Manufacturing Technology, International Journal of Lean Six Sigma and TQM Journal. These lead the rankings with 5, 5, 3, 2, 2 and 2 publications, respectively. The most prolific researchers are Rana P., Badurdeen F., Bocken N., Chiarini A., Evans S. and Short S. with 4, 3, 3, 2, 2, 2 publications, respectively.

It should be noted that 50% of the research field development came from European academic institutions. There is also an emerging contribution from Indian and Brazilian researchers. This suggests the relevance of this topic in emerging countries. Furthermore, the frequency of publications over time highlighted a research field that is in continuous expansion.

The top three keywords are “Sustainability”, “Value Stream mapping” and “Lean”. It is apparent from the literature that most approaches towards sustainable development are generic and high level. This has been confirmed by Smith et al. that highlight a lack of guidance and tools for manufacturers to identify improvement opportunities within their own factories.

Bocken et al., propose a value mapping tool that takes a multi-stakeholder perspective and considers different forms of value, such as value captured, value missed, value destroyed, and new value opportunities [56].

Paju et al. introduced a new methodology termed sustainable manufacturing mapping (SMM), which incorporates DES and life-cycle analysis (LCA) [57]. For Fearne and Martinez Value Chain Analysis tools need to adopt more holistic sustainable perspectives [58]. These include addressing external factors, such as health, environmental damage and poverty, which can offer opportunities for a chain to create shared value [59].

For Schaltegger and Burritt, opportunities mostly originate from management decisions of the focal company. This requires knowledge about i) sustainability problems, ranking of possible solutions and the assessment of consumer expectations; and ii) market strategies to make sure that the most sustainable product offered becomes a market and business success [52].

Other works have utilized tools such as Value Stream Mapping (VSM), DES, and Value Network Mapping (VNM) to model current and target states.

To summarize, existing tools generally tend to focus on just one dimension of sustainability, and fail to appoint a holistic perspective that incorporates all three dimensions of sustainability within the business planning process [60].

The literature review highlights the necessity of a tool that includes both an assessment of the sustainable external factors, and the company strategy.

1.4 Assumptions, hypotheses and research questions

In this section assumptions, hypotheses and research questions have been developed in order to define the boundaries of the study.

The results provided in this PhD thesis are only true for companies that operate in the aforementioned outlined environment and present the same or similar characteristics of case studies adopted for this study.

Assumption #1:

Due to the actual manufacturing environment of customized products, shorter lifecycles and scarcity of resources, companies are working towards:

- Sustainable production systems;
- Flexible and reconfigurable manufacturing systems;
- Digital transformation.

From the analysis of the current context and the performed literature reviews we can see that flexibility and sustainability have reached the same importance if not greater than traditional competitive dimensions (cost, quality, time and reliability). Reviewing papers it becomes clear that in the past have rarely attempted to study "flexibility + sustainability" in combination. To address uncertainties resulting from globalization and rapid climate change, organizations in the present era need to embrace sustainability and flexibility. Furthermore while traditional dimensions have been well established; flexibility and sustainability require more development. Therefore we can deduce the following hypothesis:

HP1: Sustainability and flexibility are the current strategic manufacturing dimensions/priorities, which are important in creating value for companies

Because of this, the first research questions we want to investigate is:

RQ1: What are the emergent manufacturing competitive priorities/dimensions?

Company strategy to achieve a competitive advantage is composed of i) decision making, ii) business driver identification and iii) the ability to shape strategic priorities that affect the market, environment and company itself.

Starting from previously established surveys, we want to investigate if strategy and competitiveness are associated with specific strategic priorities. These dimensions include concepts such as sustainability, flexibility, cost, quality, time and reliability.

Manufacturing supply and value chains require different assessment and evaluation of these strategic dimensions. The aim of this research question is to determine if actual flexibility and sustainability are emergent competitive dimensions for supply and value chains.

Assumption #2:

Flexibility in manufacturing systems is not a completely new topic, but due to the current market situations and the enhancements in manufacturing technology and information systems, its importance increases and different types of flexibility could have an impact on all manufacturing systems. This becomes even more important when considering the potential of smart machines interacting with humans (such as cyber-physical production systems), and the possibility of increasing connectivity and data accessing through technologies (such as the industrial internet of things), which offer an increase in flexibility. Due to the various possibilities it is important to understand which kind of flexibility is needed for a specific problem. Therefore we can deduce the following hypothesises:

HP2.1: Flexibility is a multi-dimensional and situation specific concept

HP2.2: There are different types of flexibility that have an impact on the manufacturing system (especially the emerging ones)

HP2.3: Flexibility improvement can be easier achieved by using CPPS

By consequence, the second research question concerns flexibility:
RQ2: How does flexibility impact on manufacturing companies?

Starting from case studies, a flexibility model is designed to present a clear definition of the different characteristics of manufacturing flexibility. It takes into consideration both external and internal factors, which have an impact on the company and the manufacturing strategy.

The goal of the flexibility model is to provide a framework to support firms in making decisions and delivering value.

Therefore, the aim of this study is the impact of flexibility source factors on Industry and to investigate the relationships between different type of flexibility and new emergent technologies. The following sub-question summarizes this aim:

RQ2.1: Which are the main technologies, requirements and capabilities for the next generation of industrial systems to be more flexible and sustainable?

The aim of this research question is to introduce technological concepts of Industry 4.0 and related enabling technologies that could support decentralization, manufacturing flexibility and sustainability. Their application allows orchestrating and executing production processes with the aim of supporting individual production, small lot sizes and batches and providing advanced decision support. The final aim is to identify and define digitalized requirements for specific types of flexibility that have an impact on the manufacturing system starting from an analysis of potential improvements of current Manufacturing Execution Systems (MES).

Assumption #3:

In the last few years, sustainability has caused much interest and has driven companies to re-engineer their processes and products with the aim of achieving i) greater efficiency from materials and resources and ii) an economic value from waste. This change brings about a better awareness of the production cycle, and material consumptions by reducing resources (energy and water), emissions and the production of products, all of which are sustainable in the whole life cycle. An additional step in the sustainable development is represented by the so-called Industrial Symbiosis (IS), this involves the collaboration between two or more industries, which with specific agreements support the exchange of waste and by-products to be used as raw materials. Therefore we can deduce the following hypothesises:

HP3.1: Practical implications of industrial symbiosis are positively related to industrial sustainability path and development

HP3.2: There are long-term economic benefits in support of *Industrial symbiosis*

RQ3: How does sustainability impact on manufacturing companies with regard to industrial symbiosis implementation?

The scope of this research question is to define if there are individual or specific behaviours, which may support IS. The implications of such an approach could be beneficial for industrial sustainability and provide information for product and process design, waste exchange, taxes, subsidies, business relations and other issues related to the environmental performance of firms in the industrial symbiosis network. A simulation model has been developed to analyse and improve insight into an industrial symbiosis context with the aim of moving beyond the static representation of the environmental-economic variables and deal with the system's dynamic complexity.

To summarize, the following Table 5 shows hypothesises and research questions that we have deduced.

Table 5 Hypothesises and research questions

Hypotheses	Research Questions
HP1: Sustainability and flexibility are the current strategic manufacturing dimensions/priorities, which are important in creating value for companies	*RQ1:* What are the emergent manufacturing competitive dimensions/priorities?
HP2.1: Flexibility is a multi-dimensional and situation specific concept *HP2.2:* There are different types of flexibility that have an impact on the manufacturing system (especially the emerging ones) *HP2.3*: Flexibility improvement can be easier achieved by using CPPS	*RQ2:* How does flexibility impact on manufacturing companies? *RQ2.1:* Which are the main technologies, requirements and capabilities for the next generation of industrial systems to be more flexible and sustainable?
HP3.1: Practical implications of industrial symbiosis are positively related to industrial sustainability path and development *HP3.2:* There are long-term economic benefits in support of Industrial symbiosis	*RQ3:* How does sustainability impact on manufacturing companies with regard to industrial symbiosis implementation?

1.5 Purpose

The aim of this PhD thesis is to investigate the relevance of flexibility and sustainability within the smart manufacturing environment and understand if they could be adopted as emerging competitive dimensions and help firms to take decisions and delivering value.

Survey and case based researches are utilized with the aim of analysing global behaviour and understanding specific case studies. This combined research methodology aligns and compares macro-behaviour with micro-attitude. After the analysis of flexibility and sustainability relevance, we move on to analyse their application to physical supply chains.

Flexibility: we start by investigating the topic of manufacturing flexibility to develop a framework, which allows companies to identify the impact of flexibility on their environment and processes. The performed literature review has shown that the topic is extensively covered but there is a lack in identifying the factors, which could cause a flexibility demand. A flexibility model is developed, showing a possible identification of the four main flexibility types for manufacturing systems, which can be clearly defined and delimited from each other. It also shows that a general framework could be used to highlight the relationships between flexibility demand and flexibility type.

Case studies allow identifying pressure and challenges, in terms of flexibility demand that has an impact on the company environment. And starting from these trends, define specific flexibility types and capabilities that are essential for driving companies to reconfigure their processes.

Sustainability: what is the capability needed for achieving competitive advantage in material efficiency, energy consumption, closed-loop control at industrial system level and competitiveness for improving sustainable performance. While it is not exactly clear what that transformation path will look like, it is growing clearer what action is needed at material, product, process, plant and system of production levels. IS presumes that industries collaborate intentionally and organize themselves in order to not only reach a better use of materials, but also a partnership that permits them to share strategies and objectives. With this in mind, the adoption of the model based research for IS examines different strategies, creating a dynamic environment for agents, which can actively behave in the system and interact with each other.

2 Methodology

2.1 Research strategy

The literature on operations management is constantly evolving from the concept development to methods and tools. We can also observe a relevant shift to innovative technologies and production processes, which increase the level of complexity. In addition, globalization and the very demanding customer have intensified the competition between manufacturing companies not only in the domestic market but also in the whole world.

Today, companies compete both with external factors and internal such as the utilization rate of production resources. These competitive priorities involve the traditional ones such as cost, time, quality, reliability and the emergent ones such as flexibility and sustainability. Previous studies on traditional competitive priorities suggest that manufacturing capabilities are built over time involving: i) a strong basis of quality; ii) delivery; and iii) cost efficiency. In order to prove the relevance and the evolving role of flexibility and sustainability in the current digital manufacturing environment, literature suggests the application of research tools such as survey based approaches, which allow gathering data with the aim of verify the adequacy of contents. Because of the novelty of the digitalization concept within manufacturing companies, we decided to draw our research from previously established survey results.

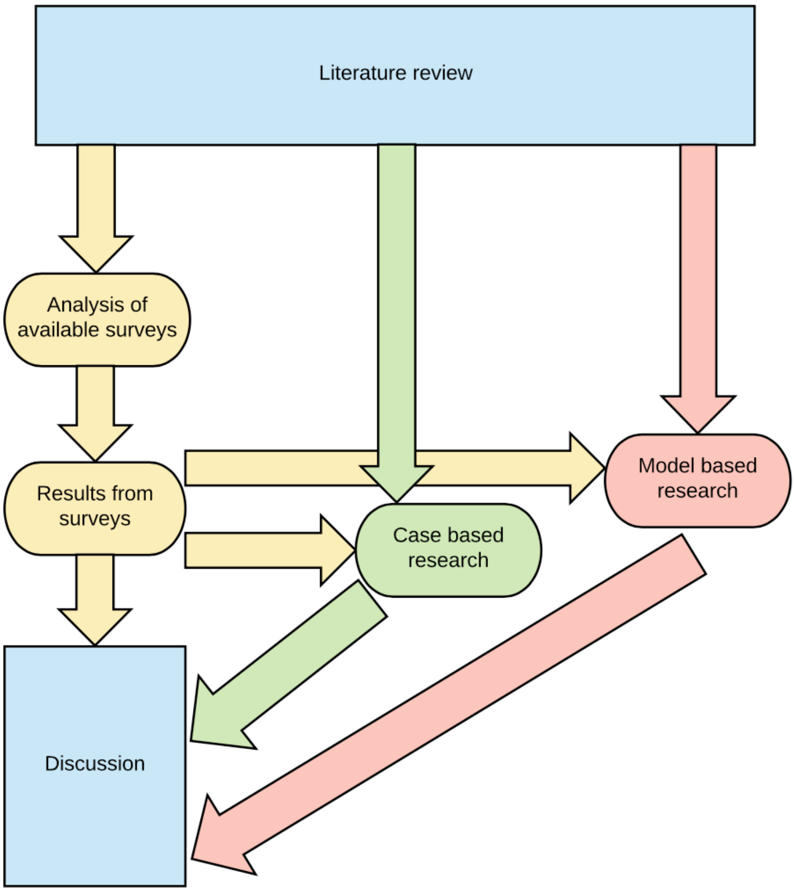

Figure 6 Research methodology adopted for this thesis

Company strategies and competitive dimensions can critically change from one industry to another; for this reason and in order to enhance our research, we decided to use the survey results with the aim at studying specific cases belonging to various industrial sectors. We selected an automotive components company, a white goods company, a food company and a soft drink company due to their characteristics and we have validated our results from these various industries towards adopting a case based research (CBR).

CBR is one of the most powerful research methods in the operations management field, especially for theory building purposes. However, CBR can also be used for testing, extending or refining theories, above all in strategic and complex topics. Finally, we adopted a model-based research to conceptualise specific behaviours. We have assumed the use of model base research in order to analyse the evolution of strategies, due to the adoption of case studies, which are not longitudinal.

Therefore, we use a mixed research methodology based on survey, case study and model, which is depicted in Figure 6. This mixed methodology is adopted with the scope of overcoming limitations of individual methods.

Survey based research visualizes, shares and generalizes results, while case based research permits a better comprehension of the connections between companies and environment. Finally model based research is the better tool for the conceptualization and validation of specific behaviour.

To summarize, we use a top down approach, we start with the results from established surveys which describe the high level dynamics adopted in the manufacturing environment, then we increase the level of detail analysing specific case studies and finally model based research allowing the description of the characteristics of the operational process or decision problem that is going to be studied.

As shown in Table 6, from the survey we expect the research answers to identify competitive priorities based on business strategy and define improvement goals associated with these competitive priorities.

While, from the case studies, we expect to verify if such competitive priorities are meaningful and serve to see how companies face these issues.

From the model-based research, we expect to analyse a conceptual model of the problem under study, assuring that current tools and analytical methods can provide a reliable solution. The relevant aspect of such methodology is that it could capture particular characteristics of real life occurrences belonging to the studied issue.

Table 6 Mapping between research questions and methodology

Research questions	**Expected results**	**Methodology**		
		Survey based research	Case based research	Model based research
RQ1: What are the emergent manufacturing competitive dimensions/priorities?	i) Identification of emergent competitive priorities in the smart manufacturing environment; ii) Definition of improvement goals associated with these competitive	X	X	

	priorities.			
RQ2: How does flexibility impact on manufacturing companies?	Definition of flexibility source factors, which implicate different flexibility types;	X		
RQ2.1: Which are the main technologies, requirements and capabilities for the next generation of industrial systems to be more flexible and sustainable?	i) Identification of the core technologies, which can lead to an analysis of the potential improvements of current Manufacturing Execution Systems (MES); ii) Definition of reconfiguration use cases, which supported by digitalized opportunities allow achieving specific type of flexibility	X		
RQ3: How does sustainability impact on manufacturing companies with regard to industrial symbiosis implementation?	Define if there are individual or specific behaviours, which may support industrial sustainability. Define beneficial for the industrial sustainability and provide information for product design, process design, industrial location, waste exchange, taxes, subsidies, business relations and other issues related to the environmental performance.	X	X	

2.2 Survey based research

A survey-based research aims at gathering high volume of information, which concerns people, companies, society and environment. The survey-based approach is used in a wide range of applications such as politics, medicine, social and business science, economics and engineering fields. A survey can be lead by different organizations such as private or public companies and research institutes. Generally, a survey-based approach focuses on the gathering of information, data and opinions and it is based on the application of a specifically designed questionnaire.

Survey research distinguishes between exploratory, confirmatory and descriptive survey research:

- *Exploratory survey research* is used in the early stages of research, when the aim is to obtain an initial insight on a subject; this can be used as the basis for a more detailed survey. In the early stages, exploratory survey research allows us to define the data to be analysed with respect to the phenomenon to be studied. It can reveal preliminary evidence of association among concepts. Additionally, the valid boundary of a theory can be explored. Sometimes the data used in previous studies is used in exploratory survey research.
- *Confirmatory survey research.* This is when knowledge of a phenomenon has been established in a theoretical form. In this case, data collection is done with the direct purpose of testing i) the capacity of the concepts, ii) hypothesised connections between the concepts, and iii) the valid boundary of the models. Consequently, we must carefully consider all of the error sources.
- *Descriptive survey research* is used to understand the importance of a certain event and describes the distribution of the event in a population. Its main purpose is not theory building, even though it can provide useful clues both for theory development and for theory refinement.

In general, the necessary activities for designing a survey are:

1. *Preparation phase:* this focuses on i) the scope of the survey, ii) the sample definition, iii) the questionnaire design and iv) the interview set up.
2. *Execution phase:* this focuses on the interview, which could be conducted face to face or by telephone, mail, or Internet.
3. *Analysis phase*: this concentrates on the data, statistics and results created and analysed in order to assess the original scope.

2.2.1 Preparation phase

The scope of the survey-based approach is to analyse a phenomenon showing beneficial answers, which could resolve the original purpose. Before the gathering of data, it is necessary to design the survey, bearing in mind survey scope, statistic units, tools and sample.

Some surveys analyse global behaviour, oriented to the whole statistical universe. In this case the sample corresponds to the all-statistical units. On the other hand, if a survey is based on a subset of the statistical universe, it is necessary to choose the proper statistical units.

It is fundamental to design the structure of the interview, on the base of the survey scope. The interview can be:

- *A structured interview*: this is made up of an interviewer and interviewee;

- *Questionnaire based*: this concerns a more independent survey. This means that the interviewee reads and answers autonomously.

In either case, the range of answers must be standardized, in order to simplify the next phase, which is based on the data analysis.

In the structured interview, the interviewer not only reads questions, but also proposes a range of answers. In this case the interview is also called “closed”, on the contrary an “open” interview allows the interviewee to answer independently. Obviously in the “open” interview, the analysis phase is more complicated due to the interpretation of data. Additionally, a survey could be made up of both closed and open interviews; therefore utilizing both structured and independent answers. The interview is a critical phase, and should be designed considering in the following guidelines:

- The survey topic (must be clear to the interviewee);
- Data gathering (should be a simple task);
- Data depiction;
- Balance of questions;
- Comprehensive answers (in case of “closed” interview);
- Logical sequence of questions.

2.2.2 Execution phase

The execution phase concerns the real interview. Based on the analysis of the sample, it is possible to choose the proper interview method. The interview can be conducted by phone, in the work place, online or by mail; but it is important to reach as many interviewees as possible.

Moreover, in order to increase the response quota, it is possible to implement the following guidelines:

- Keep the questionnaire as brief as possible;
- Give economic incentives;
- Give gift incentives;
- Create affiliation or partnership.

2.2.3 Analysis phase

Analysis phase proceeds with the examination of data and with the categorization of the answers. The categorization takes into consideration the relevant characteristics of the data. It is important to cluster data in order to simplify the analysis phase. Data analysis can be lead by two approaches: preliminary data analysis and hypothesis testing.

To gather information from the characteristics and properties of the collected data some preliminary data analyses are usually performed before hypothesis testing. This allows the understanding of how well the coding and entering of data has been done, how good the scales are, and whether there is a suspicion of poor content validity or systematic bias.

Furthermore hypothesis tests can be grouped into: parametric and non- parametric groups. On the one hand parametric tests are more powerful because their data is typically derived from interval and ratio measurements where the likelihood model is known (with some exceptions). On the other hand, non-parametric tests are also used, with nominal and ordinal data.

Concluding, because of the novelty of digitalization in manufacturing companies, we decided to draw our research from the results of available surveys, which make us to conceptualizing, sharing and generalizing results, which will be tested using case and model based researches.

2.3 Case based research

The case based research (CBR) represents a widespread strategy in the operations management field. It is a research methodology compatible with a variety of purposes; it can be used for supporting a positive, qualitative or interpretative thesis. CBR is established on "field" data gathering, which is useful in understanding specific companies' behaviour. Nevertheless, there could be practical difficulties associated to its effectiveness and rigor.

This research methodology is often associated with the description and building of theories, and it is also used for highlighting hypothesis development and the exploration of research areas, which need improvement. It is an empirical research method, which aims at:

- Investigating a phenomenon within its real-life context;
- Investigating a phenomenon, when boundaries between it and the environment are not clear.

For these reasons, CBR should be chosen when the boundary conditions are highly relevant with the investigated phenomenon. The phenomenon should be analysed in its specific context, in fact, if an event can be isolated the best research methodology would be an "experiment". The success of such a method is due to its application for both technological and organizational problems. In order to face the increasing changes in production systems, researchers need a field-based research method. There are many challenges associated with the adoption of CBR: i) it is time consuming, ii) it needs expert interviewers, and iii) results are often context specific. Nevertheless, CBR's results can have a huge impact. In fact using open questions (despite all the implications) rather than a standard questionnaire, new theories and intuitions can be developed and CBR can achieve different aims such as:

- Exploration: it is used in the early stages of research, when it is necessary to develop new ideas, research questions and concepts.
- Theory building: it is used for the development of new theories; in fact "nothing is so practical as a good theory" [61]. It is impossible to contest data without theory.
- Theory testing: it is used for testing complex issue such as strategy implementation; often it is matched with survey-based research.
- Theory extension/refinement: is used as a follow-up to survey based research in an attempt to examine and validate previous empirical results.

2.3.1 Choosing cases

What is the ideal number of cases? The fewer case studies analysed results in a more in-depth breakdown as a single CBR often implies different subsets of issues. Single CBR are often used in the longitudinal research. Furthermore, the number of cases varies with respect to the typology of industry. Single CBR presents some limitations:

1. It is difficult to generalize conclusions and outcomes in other industries;
2. Risks of misjudging a single event or exaggerating easily available data.

On the other hand, the adoption of multiple CBR can overcome these issues, even though there is the possibility of misjudging/exaggerating data, these effects are mitigated by the comparison of all the multiple cases, so despite the reduction in the depth of study an increase in the accuracy of results is achieved.

2.3.2 Longitudinal or retrospective cases?

Another possibility for CBR is the choice between longitudinal or retrospective cases. Retrospective cases allow more control in case selection, for example it is possible to identify cases that reflect either success or failure only in retrospect.

The longitudinal research is particularly important, because when more time is used to analyse phenomenon there is a greater opportunity to observe connections between cause and effect.

However, there could be problems with historical data. For example, interviewees may not remember important events, and if they remember past data, they could be polarized. Another particular problem is post-rationalisation, the interpretation of events in a different manner than they would have been at the time.

2.3.3 Cases selection and sampling

If multiple CBR is used, it is important to define case selection or sampling; generally, this involves two actions:

1. Define the boundaries of the research and link them to the research questions;
2. Define a framework in order to discover, confirm or quantify constraints that underpin the study.

The traditional sampling implies a case selection extracted at random, but often in CBR the case selection is defined using different criteria. When building a theory from case studies, case selection using replication logic rather than sampling is used.

2.3.4 Sample of cases

As stated above, four manufacturing companies were analysed: i) an automotive components company; ii) a white goods company; iii) a food company; and iv) a soft drink company. The four case studies have been chosen for these macro-characteristics:

- Show strong orientation towards sustainable issues;
- Focus on relevant flexible and re-configurable issues;
- Represent a miscellaneous sample, showing both discrete and continuous processes.

Each company and their intrinsic aspects will be analysed in the subsequent sections.

The tool used for conducting interviews is the Value Modeler, which has been co-developed with Siemens MES Division. The structure of the tool follows the Manufacturing Value Modelling Methodology (MVMM), which presents the following hierarchical approach:

- *Trend*: represents the market tendencies and the specific environment in which the company works;
- *Implication*: describes the business impact on the company driven by the trends, and states how the trends are affecting the company strategy;

- *Possibility*: identifies: i) responses by the company in addressing an opportunity or risk resulting from the implications; ii) actions taken to capture an opportunity or reduce a risk.

Based on this model, interviews and focus groups were conducted with Siemens industrial experts in order to develop a questionnaire, whose sections follow the MVMM.

Consequently, semi-structured questionnaires were submitted to managers belonging to the manufacturing companies. During the assessment, each manager highlights company strengths/weaknesses and identifies strategic business requirements and impediments to its strategies. For each of the three questionnaire sections, managers can measure company process or activity evaluating the current state and the target state with a score from 1 to 5 that reflects five maturity levels. The maturity model used is "Gartner Maturity Model" (Figure 7). This measures the current state of the company and is based on 5 increasing maturity levels that describes how an operation is performed:

- Stage 1 React: companies focus on operational activities and plan at a factory or distribution level, with all locations focusing on their own objectives;
- Stage 2 Anticipate: the objective of supply planning evolves from covering existing orders to attempting to match projected supply to forecast demand;
- Stage 3 Integrate: organizations seek to fully integrate their demand and supply plans to create a volume and service-oriented response to anticipated demand;
- Stage 4 Collaborate: organizations have achieved functional excellence in collaboration and supply planning;
- Stage 5 Orchestrate: the boundaries between demand and supply planning become blurred as the functions work together to support value chain orchestration.

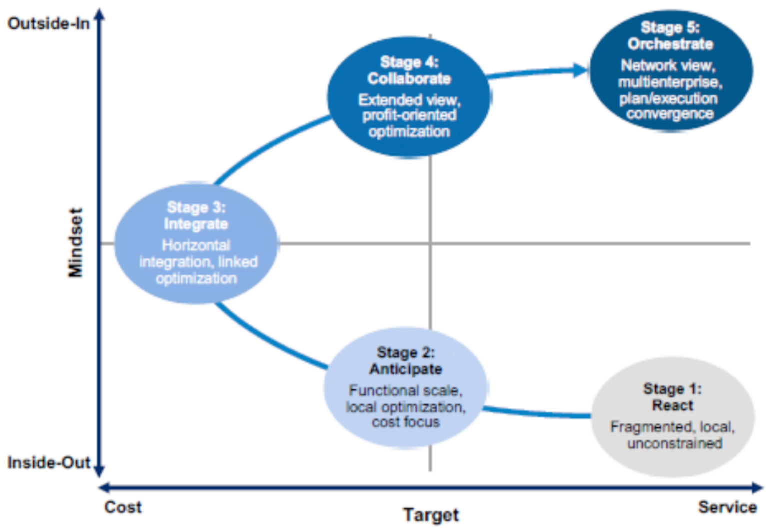

Figure 7 Gartner Maturity Model

The assessment of these case studies was done with the Supply Chain Manager (SC Manager) and Research & Development Manager (R&D Manager) of the companies. These roles were chosen because the SC Manager has a vision of the whole processes of the SC in terms of materials, equipment, suppliers and overall performance, while the R&D manager investigates technology development, concept development, and new product development.

We decided to use Value Modeler tool, because it increases the efficiency, accuracy and reliability of data collection. Furthermore, it gives us a better picture of a "Day-In-The-Life" of both executives and operational managers resulting in two different points of view of the company strategy.

Finally, the method behind the tool is a structured approach with the scope of bringing out business strengths/weaknesses, goals, objectives and future outlooks; a related aim is to have a clearer overview of both the strategic and operational levels of the company.

The innovative aspect of the proposed approach is full correlation. It is relevant to underline that the model has a closed loop approach, in fact starting from "trend", it is possible to understand what activities and what business areas need to be improved to achieve the company objective linked to that path. There is also an option to start from "possibility" and go back to the related "trends" and "implications". Furthermore, all these processes are controlled and monitored constantly.

2.3.4.1 Case 1: Automotive supplier industry

The first case study was carried out in the automotive supplier industry, which reacts strongly to economical crisis. It is estimated that by 2020 there will be 108 million manufactured vehicles and around the 40% of them will be destined for the Asian market. The market share will change as developing countries, such as India, Brazil and Russia will significantly increase their production, while in other nations production will only increase slightly or even be reduced. The automotive supplier industry should benefit from increasing automotive demand, market growth and technological advancement. The automotive supplier industry will reach 23.1% of growth by 2020.

In our research, we focus on the automotive supplier industry, which is a crucial element of the industrial sector with a large number of small and medium-sized suppliers. Particularly, the automotive supplier industry is often responsible for new automotive technologies worldwide [62]. With this in mind, most of the vehicle parts are engineered and manufactured by the suppliers. Automotive suppliers with the original equipment manufacturers (OEMs) are involved and responsible for development and design projects.

Furthermore, automotive supplier industry products are generally highly customized components or integrated subsystems (such as power steering, breaking and air-conditioning) that require precision technology and engineering [63].

For these reasons we decided to include this industrial sector in our research, as it seemed a suitable case in order to explore the meaning of flexibility. It is advanced in sustainable production in many respects and demands sustainable processes for the entire supply chain, too.

2.3.4.2 Case 2: White goods industry

As in the other industries, the white goods sector is strongly influenced by the current smart manufacturing environment. White goods are defined as refrigerators, water heaters, freezers, air conditioners, washing machines, dishwashers and clothes dryers.

In our research, we focus on white goods companies, because they are working in order to reduce time to market and related costs for new product introduction. Because of this, industries need new ways to manage product development.

The current white goods company usually uses one line to produce different products, as a component can be adopted in various platforms. This can also occur for technologies and products [64].

Flexible automation supported by robots is a suitable solution not only for white goods factories but also for their suppliers. This aims to increase ergonomics, process quality and efficiency, as well as cost and flexibility.

In recognition of these characteristics, a white goods company has been chosen in order to analyse the flexibility demands of this sector and understand how it faces sustainable issues. In addition, there are a number of environmental aspects that are common to all white goods, such as the manufacture of the white metal cabinet, the degree of reparability and durability, recovery at end of use, packaging and consumer education [65].

For these reasons the white goods industry needs to re-think their business models, processes and products. Strategies, which were previously considered less appropriate (i.e. regional or global strategies) for white goods, may now have become increasingly viable under the ever-changing industry conditions.

2.3.4.3 Case 3: Food sector

The food industry is considered one of the most important sectors of the current economy. It is clear in this segment that there is an increasing level of variability in terms of demand, volume, process, manufacturing technology, customer behaviour and supplier attitude.

The main production processes within food companies are: raw material processing and packaging. Therefore, there is an extra complexity in the management of these processes, especially in order to decouple the two stages due to the creation of intermediate storage between them.

To deal with the short lead times and with customer-specific packages for end products, manufacturers often have make-to-order strategies on the packaging level. This puts additional pressure on the production system, as it becomes partly make-to-order (packaging stage), and partly make-to-stock (processing stage). The intermediate storage in these industries is normally constrained in capacity and time. Capacity is not only constrained by a limited number of tanks, but also because quality demands do not allow concurrent usage of them. Time constraints result from perishability of the basic food product, which restricts the time until packaging.

In our research, we focus on the food segment, because it is facing particular global challenges that can be met with support by information technologies (IT) on a level even beyond today's advanced IT utilizations [66] and where the new paradigm of Industry 4.0 can represent an interesting evolution. Specifically, the food industry has recently changed from a supply-based approach to a demand-based approach, the so-called "chain reversal", this is where the consumers dictates what they want to eat [67], [68]. Food and drink consumption differs among individuals; this means that production should be tailored to customer demand. In order to realize this vision, elements such as machines, tanks, storage systems, and utilities must be able to share information, as well as act and control each other autonomously [69]. This results in a system in which all processes are fully integrated.

Finally, because the products are configured to respond to the preferences of individual users, production must be more flexible [70] than in the past.

We focus on the food industry because it shows discrete and processing stages, capacity, time and quality constrains as well as highly tailored customer demand. All these factors implicate a specific need for flexibility.

2.3.4.4 Case 4: Soft drink sector

This sector is part of the Consumer Packaged Goods Market (CPG). The CPG is a wide market, that amounted to 3.0 Trillion US$ Global MSP Value in 2016. The products belonging to this market are the type of goods consumed every day by the average consumer. The goods that comprise this category are ones that, need to be replaced frequently, compared to those that are usable for extended periods of time.

This sector is not just growing in consumption but it is also constantly evolving. For these main reasons, companies belonging to this sector are forced to invest in research, innovation and development in order to be competitive and respond to market requests [71]. At the same time, new marketing strategies are required and are often more important than the product itself in satisfying new consumers' needs [72].

In this context, over the last years, much attention has been given to development of new products. These focus more on the nutritional and functional aspects whilst paying attention to the sustainability of the whole supply chain.

Furthermore, different trends are currently affecting this industry, such as: (i) the increase in Health-Conscious Consumers and the rise of healthy foods and beverages [73], (ii) the growing consumption of Premium Quality products [74], and challenges due to legislation & compliance to standards [75], [76] (iii) the high complexities due to the huge packaging variety [75], [76] (iv) the large price increases in raw materials in recent years and (v) the decreasing willingness to pay for the consumption of standard food and beverage (F&B) products [77].

In our research, we focus on soft drinks companies, because the environmental regulations and the sustainable developments are forcing industries to assess, optimise and improve their processes in order to minimise costs and increase the efficiency of environmental sustainability. This effect is even more evident in the food and beverage industries due to the high impact that this sector has on industrial sustainability, considering the primary role of packaging systems, the huge water consumption both for the production and the cleaning processes or the energy utilization related to the treatment plant or to the raw material production.

Thus, the main objective of considering this industry is to understand how companies operating in the soft drinks sector could benefit from the sustainability aspects, to enhance their operations.

2.4 Model based research

In the last decades, model based research (MBR) has been emerged as a strong academic research line, which works on more idealized problems and therefore builds theory. MBR concerns quantitative models, which are developed, analysed and tested based on the relationships between control and performance variables. A controlled variable is one, which the researcher holds constant during an experiment. It is also known as a constant variable or simply as a "control". The control variable is not part of an experiment, but it is important because it can have an effect on the results. Performance variables can be physical variables such as the level of inventory, the utilization rate or economic variables e.g. costs, revenues and profit. The MBR design is based on the following steps:

1. Conceptual modelling;
2. Scientific modelling;
3. Analysis, solution, and proof;

4. Insights.

2.4.1 Conceptual modelling

The MBR starts with a description of operational characteristics or decision problems. The conceptual model description should use concepts and terms, which have been accepted and understood by the literature. Generally, the issue under study is a variant of a current and recognised problem. This allows connecting such problems to the literature. It is also necessary to describe the whole theories that are assumed in order to develop the conceptual model. The relevance of the conceptual model is established with respect to the alignment of "the issue" versus "the current literature". We can distinguish two types of contributions:

1. A study based on a new variant of a problem, solved using traditional techniques;
2. A study based on a known problem, which has been studied before but adopting new methods or techniques.

2.4.2 Scientific modelling

The second phase of MBR is the specification of the scientific model of the process or problem. The scientific model must be represented in formal mathematical terms in order to simulate the model being studied. Furthermore, the relationships between various variables need to be explained. The scientific quality of the model can be defined with respect to different characteristics such as i) level of innovation, ii) the compactness of the model, and iii) the degree to which the model can be studied analytically. Each scientific model should underline theories assumed with respect to the conceptual model. The analytical research builds an idealized model, which represent a specific problem and finds a solution adopting available analytical methods and tools. The validity of the idealized model is one of the main aspects of the study. Validation means that the model captures some of the characteristics of each of the real life occurrences. So validation can be achieved as follows:

- It may refer to scientifically accepted axiomatic descriptions of the system studied that contain evidence of the occurrence of the characteristics in real life;
- It may refer to published empirical research that shows the existence in real life of the characteristics captured in the model;
- It may refer to earlier published research that uses the same modelling assumptions.

2.4.3 Analysis, solution, and proof

Researchers can analyse scientific models using algebraic, numerical or simulation techniques. The aim of using algebraic technique is to develop solutions, which are in the terms of "closed-form". "Closed-form solutions" are expressions, which allow the correlation of whole variables and only one mathematical function can be included. For more complex problem, numerical techniques must be adopted. In the case in which simulation is used, experimental design and statistical analysis must be introduced. The scientific quality of the research is mainly determined by the "optimality" of the result, given the scientific model. Proof generally can only be delivered with mathematical analysis.

2.4.4 Insights

After the analysis and solution development, it is important to collect contributions and intuitions from the study. This means that a comparison between the conceptual and scientific model is needed in order to develop knowledge.

3 Results

3.1 Results from previously established surveys (RQ1)

The world and society are now constantly evolving through scenarios of global change and development, which have a direct and indirect impact on manufacturing companies. The related manufacturing value chains require different assessment and evaluation of strategic dimensions. To achieve a competitive advantage, company strategy is viewed as the ability to make decisions, the identification of business drivers and strategic dimension modelling that can affect the markets, the environment and the company itself.

Thus in a global competitive market, companies are looking for a good strategy which transforms into a competitive advantage. A good strategy can be defined as the sum of all needed actions, which achieve specific objectives over time. Therefore, the strategy is responsible for i) time evolution, ii) goal achievement and iii) competitive dimension (priority) identification. Competitive priorities are based on all subsequent activities in the supply chain from design to distribution of resources.

The traditional competitive priorities include quality, cost, speed, delivery and efficiency. Hayes and Wheelwright, and Leong [78], [79] describe these competitive dimensions as “strategic priorities or goals or ways that are selected by companies to maximize competitiveness in the market”.

During the last few years, various researchers have assumed additional competitive priorities and proposed some methods to evaluate their performances. What’s more, even though there has been much theoretical reasoning on the number of competitive dimensions, only a few papers provide an empirical validation.

With this in mind, the preliminary scope of this PhD thesis is to investigate and define the emergent competitive dimensions/priorities, which can help companies achieve a competitive advantage in the digital manufacturing environment.

As previously stated, we decided to draw our research from established survey results. We decided to analyse two specific papers in this field:

1. The industrial point of view “Towards the identification of important strategic priorities of the supply chain network An empirical investigation”, Tsironis and Matthopoulos (2015) [80];
2. The literature point of view “The evolution and future of manufacturing: A review”, Esmaeiliana, Behdadb, Wangc (2016) [81];

After the survey analysis, we will move to the case based research in order to empirically validate our competitive dimensions.

3.1.1 “Towards the identification of important strategic priorities of the supply chain network: An empirical investigation”

The purpose of this survey is to demonstrate what the current competitive dimensions are. 200 managers belonging to 71 manufacturing companies completed a questionnaire submitted by researchers. Then the data was analysed to create a model to pinpoint the strategic priorities needed to achieve a competitive advantage for the company.

Each manager had to assess the importance of a competitive dimension on a scale from 1 (lower) to 10 (higher). The questionnaire was composed of two parts, the first was an explorative section, which contained general information about the company (company size, sector, market etc.), and the second part, relied on the competitive dimension assessment. Managers assessed the following competitive priorities:

1. Quality;
2. Cost;
3. Velocity;
4. Flexibility;
5. Production;
6. Information technology;
7. Customer service and satisfaction;
8. Workforce;
9. Sustainability;
10. Viability;
11. Collaboration;
12. Supply chain capacity;
13. Segmentation;
14. Performance;
15. Risks.

At this point, it is important to underline that each competitive priority includes some sub-dimensions, such as the competitive priority cost, which also includes low production cost, costs reduction and waste reduction.

The results obtained, through a factor analysis, demonstrate that there are seven relevant competitive dimensions (Figure 8):

- Flexibility: linked to the ability to react to unexpected changes;
- Quality: implies quality standards of products, and quality procedure of production process;
- Waste reduction: focuses on the reduction on re-work, scrap, by-products and waste;
- Customer service and satisfaction: deals with different delivery strategies to maximize customer satisfaction;
- Sustainability: concerns all the activities needed to pursue sustainable development;
- Cost reduction: reduce costs to maximize profits;
- Efficiency: improve performance and competence.

The framework highlighted that customer service and satisfaction, cost reduction and sustainability were the critical and relevant competitive dimensions, which had a direct impact on the company’s efficiency. While, flexibility, quality and waste reduction showed a direct and positive effect on customer focus, cost reduction and sustainability.

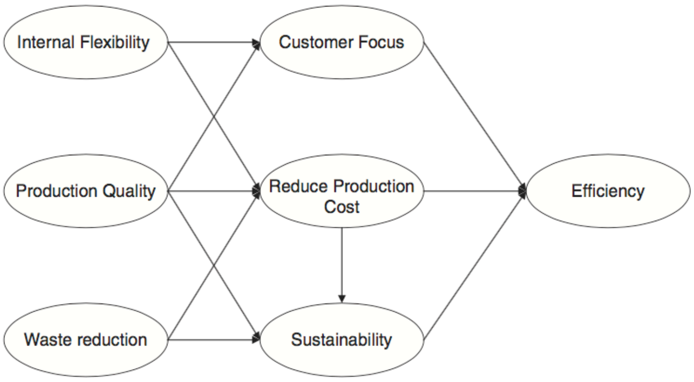

Figure 8 The framework of the strategic priorities of a SC network proposed by Tsironis and Matthopoulos

As highlighted before, the identification of competitive dimensions is essential in order to:

- Define a proper strategy;
- Clarify the company priorities and performance issues;
- React to competitors in an effective way;
- Identify the most relevant activities/practices;
- Align the company and manufacturing strategy.

To conclude, the results of this survey confirm that sustainability and flexibility are equally as relevant as the other five competitive dimensions for manufacturing companies. The following scope will be to analyse if these topics are also relevant from a literature point of view.

3.1.2 The evolution and future of manufacturing: A review

As new production paradigms are introduced, supply and value chains explore how the emergent competitive priorities influence current strategies. This survey focuses on the evolution of manufacturing systems approaching the new era characterised by digitalization and innovative technologies.

The purpose of this work is to define the priorities needed in this changing field, which are depicted in Figure 9.

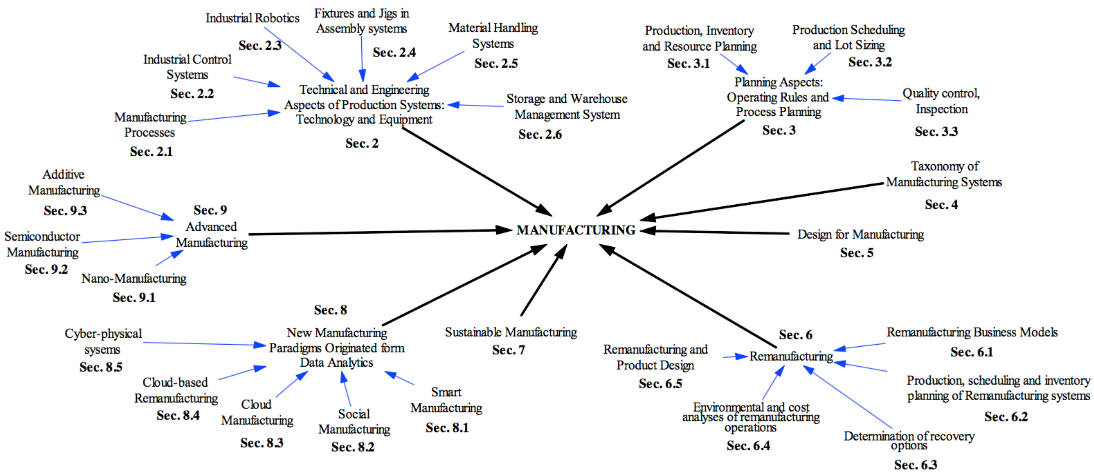

Figure 9 The scope and structure of the survey proposed by Esmaeiliana et all.

As stated before, this survey studies “the evolution of research in manufacturing starting from past and current trends to future developments”. Therefore, this data is used in order to confirm the relevance of our topics (flexibility and sustainability).

Figure 9 depicts the results of the aforementioned survey, thus we focus on:

- Environmental conscious manufacturing and sustainable manufacturing;
- Planning aspects: Operating rules and process planning
- New manufacturing paradigms originated from data analytics.

Environmental conscious manufacturing and sustainable manufacturing

Environmental regulations, customer interest in green products, scarcity of resources and potential profitability resulting from recycling are the motives for the emergence of new business models based for example on remanufacturing and sustainable production.

Remanufacturing is a production paradigm based on the reuse of materials and it is a cornerstone of the circular economy. It also represents a new business model, which aims at improving environmental and economical dimensions. It is based on the disassembly of a used product, which can be reconditioned and reused.

Thus, remanufacturing typically involves a re-think of:

- Strategy;
- Production, planning and scheduling activities;

and a complete overhaul of:

- Recovery activities;
- Environmental analysis and related remanufacturing costs;
- Applicability of remanufacturing to products.

Remanufacturing is identified as the current response with respect to i) the necessity to increase competitiveness, ii) the commitment of reducing environmental impact, and iii) the duty to minimize production costs. With this in mind, an example of remanufacturing is Xerox, a digital printing company, which has changed its business model, moving from a traditional business model based on selling products to a new one based on selling services.

Meanwhile sustainable production aims at creating alternative products, which reduce the consumption of resources and minimize unnecessary production processes, waste, toxic materials and carbon footprint. Perhaps, “sustainable business” instead of “sustainable production” would be a better term, because production represents only one step of the sustainable development. An additional distinction must be made between “sustainable manufacturing” and “green manufacturing”. The former supports the concept of “triple bottom line” while the latter mainly concerns environmental and social sustainability.

At this point it is important to underline that as this shift towards sustainability needs huge investments and product and process re-engineering, companies need to know that drivers (environmental regulations and customer interest for green products) are not the only grounds for moving towards sustainable manufacturing and that there is the possibility of achieving an economic value or a competitive advantage.

For this reason model-based research is used in order to simulate and understand, which the potential benefits linked to sustainable development could be. Furthermore, model based research allows an evaluation of complex operations such as system variables and human behaviour in order to provide a system thinking approach in all three levels of operations, facility and enterprise.

Planning aspects: Operating rules and process planning

Production systems are deeply influenced by the demand fluctuation. So new management concepts and methodologies are emerging with a related impact on planning and scheduling activities, which demand for new requirements. Concepts such as Just In Time (JIT), Manufacturing Resource Planning (MRPII), Enterprise Resource Planning (ERP), Lean, Agile, Leagile, Flexible and Kanban are developed in order to create a demand for process planning not only at the factory level but also at the device, production line and supply chain levels.

New manufacturing paradigms originated from data analytics

In the last few years new technologies and production paradigms such as CPPS, Smart Factory and additive manufacturing have been introduced thanks to technological advancement. Companies are exploring the concept of decentralized, self-organizing CPPS to build future smart factories and plants as envisioned by the platform Industrie 4.0.

The decentralized and self-organized production is based on the integration of different elements which are all intelligent, therefore each production element knows its own skill, capability, position and needs, there is no need of central coordination [82]. The advantages of this production paradigm are: i) reduction of breakdown, installation and maintenance costs; ii) reduction of engineering, reprogramming or rescheduling activities; iii) increase in flexible placement production; iv) continuous production optimization and v) customer centric approach, which supports the highly individualized and small production.

Figure 10 depicts the trend of the most recent manufacturing concepts as appeared in publications.

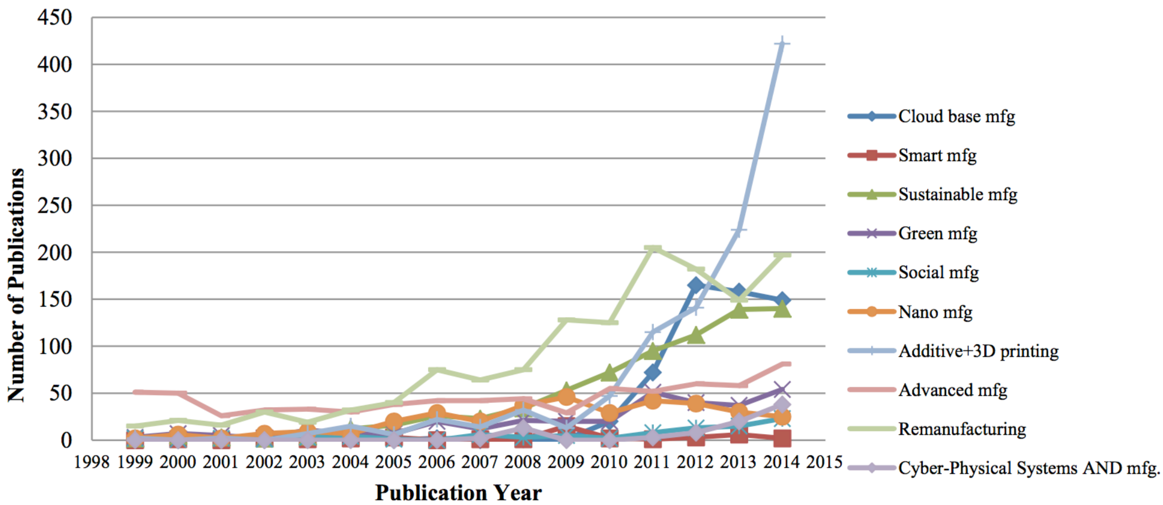

Figure 10 The trend of most recent manufacturing concepts appeared in literature proposed by Esmaeiliana et all.

3.2 Case studies results (RQ1-RQ2-RQ3)

3.2.1 Case 1: An automotive components company

The first case study was carried out in an Italian manufacturing company, which designs, develops and produces braking systems for a wide range of both road and track vehicles, and is a global leader in its sector and also operates in the spare parts market. The company guarantees the upmost safety and comfort and improved product performance thanks to process integration and optimization of the entire production cycle, from the initial design to casting and assembly, and to testing on the bench, track and road. They distribute their equipment all over the world. The plant is composed of two macro-production processes: i) foundry and ii) assembly.

In our research, we focus on this specific company because:

- It is the global leader in its sector;
- Its products are of the latest design and quality;
- It has the major market share;
- It is customer orientated.

Thanks to a constant focus on development technologies and processes, the company benefits from a strong leadership on the international scene in the research, design and production of high performance braking systems.

The high level of technology and reliability offered by the company is the result of the integrated production process that exists within the company. This includes all the phases of the manufacturing process itself, from research and development to testing, and the casting and mechanical processing stages.

Thanks to its global presence, with production facilities in Europe, the USA, Mexico, Brazil and China, the company offers a complete product range with the advantages of centralised process and product development and the benefits of a local presence. These elements enable the company to be competitive and offer a high quality of service.

Quality is one of the main challenges; the scope is to achieve "zero risk" in the products, processes and materials used and in the environment. The company strives to create a system of zero defects in all areas.

It is also very involved in the use of sustainability in its processes. Its goal is to continuously improve its performance in terms of health and safety in the workplace and environment. In particular, this involves:

- Reducing environmental impact and risks in the definition of each product and process;
- Introducing eco-compatible technologies;
- Taking adequate measures to prevent any form of pollution and accidents in its daily activities.

This is a primary goal for the company and it is committed to taking every measurement possible to ensure that it is achieved.

A semi-structured questionnaire (based on the Value Modeler methodology) was submitted to the company. Figure 11 reports the results of the assessment with respect to the analysis of trends. Starting with the company answers, it is possible to see a substantial correlation in the managers' answers, the main trends addressed are:

- Extended product variety;
- Accelerated use of new technologies;
- Shorter product life cycles;

- Environmental awareness.

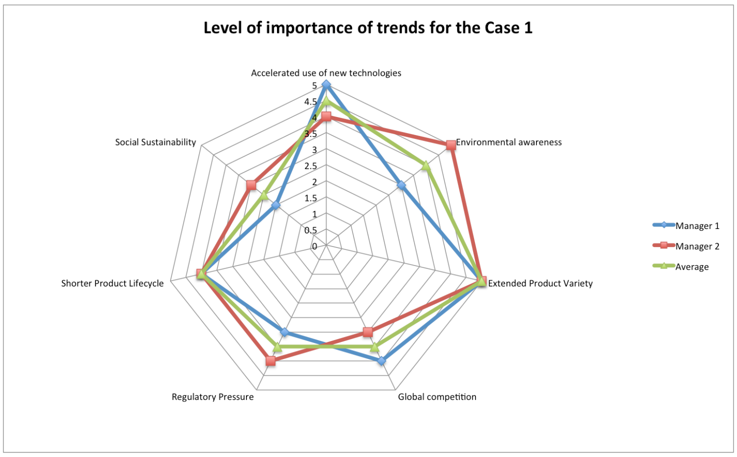

Figure 11 Trends' analysis

It is possible to categorize these contents with the following statements, which describe the company implications (Figure 12):

- *Cross-plant standardization:* addresses new emerging markets (America and Asia), opens new plants based on best practises standardization;
- *Ensure the highest level of quality:* quality data should be integrated and managed in a unique environment to allow a complete monitoring of all the executed quality operations, furthermore scrap should be examined for its causes with the aim of eradication;
- *Improve flexibility and harmonizing production landscape across plants:* this is a strategic goal and the company wants to invest on it in the near future (low pressure melting process vs traditional gravity process). It needs to produce high volumes to maintain high sales. To reach this target it has to unveil new production processes and improve its internal organization;
- *Reduce costs and improve production performance:* Breakdown and root-cause analysis are needed in assembly. Furthermore, there is the need to have an integrated logistic system among assembly and foundry business process areas in order to manage demand variability and then reduce costs.

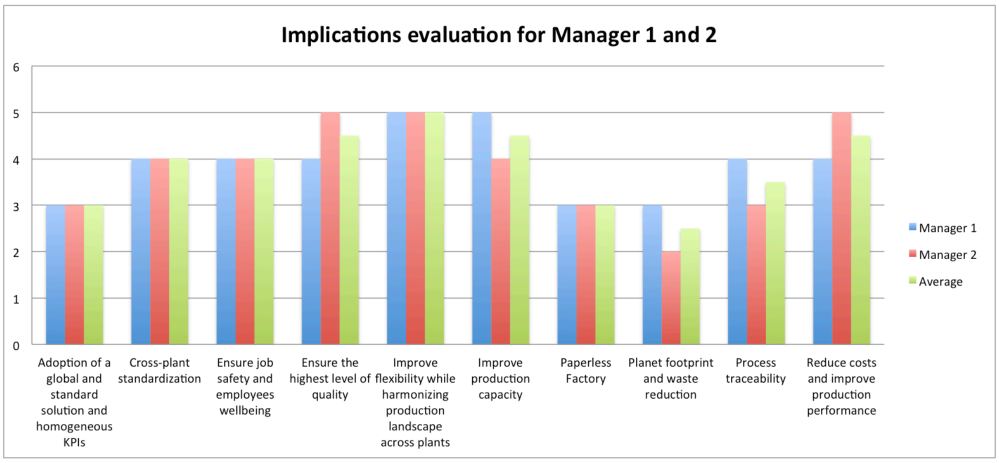

Figure 12 Implications' assessment

We have also analysed which internal activities or processes need interventions defining the current and the target state of the company (Figure 13 and 14). The possibilities addressed by managers can be grouped in three clusters:

- *"Automate data collection and reduce paperwork" and "ICT Integration":* this means implementing data analytics and integrating ICT in order to i) help make tactical and strategic business decisions, ii) interconnect system between people, process and knowledge throughout the enterprise, iii) forecast analysis for better support planning. These possibilities are very relevant for the company, as managers explained that system errors impacted strongly on customer' sales.
- *"Component traceability" and "Material genealogy"*: the scope is to track products and materials along their whole lifecycle.
- *"Optimize capacity thanks to better use of available resources" and "Sequence optimization":* these highlight the planning and scheduling problems due to various factors: i) planning in foundry is managed only by two senior people. There is no ICT tool to support it, ii) daily scheduler output is not accurate (setup missing), and long calculation times are required, which don't allow real-time tunings. Furthermore a better management of matching order with machine is mandatory in order to fulfil demand variability.

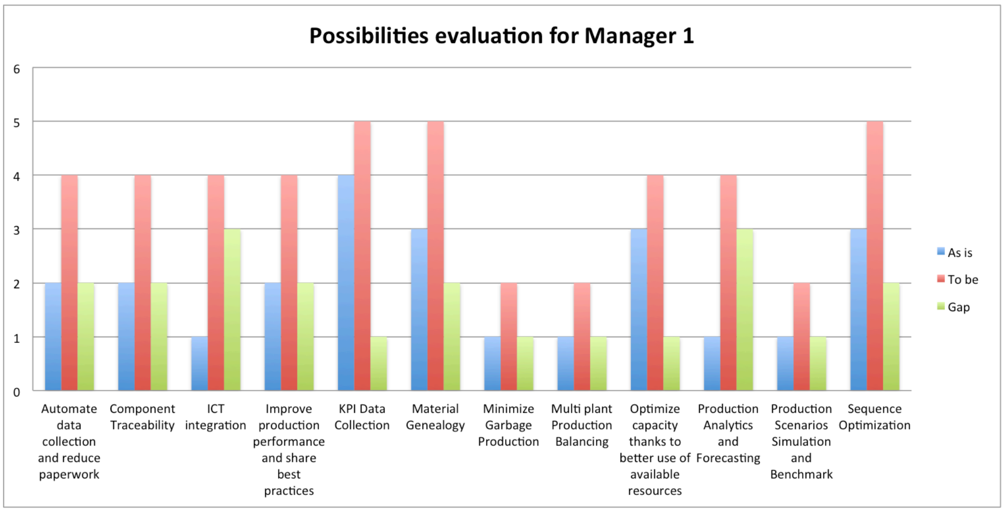

Figure 13 Possibilities' evaluation for Manager 1

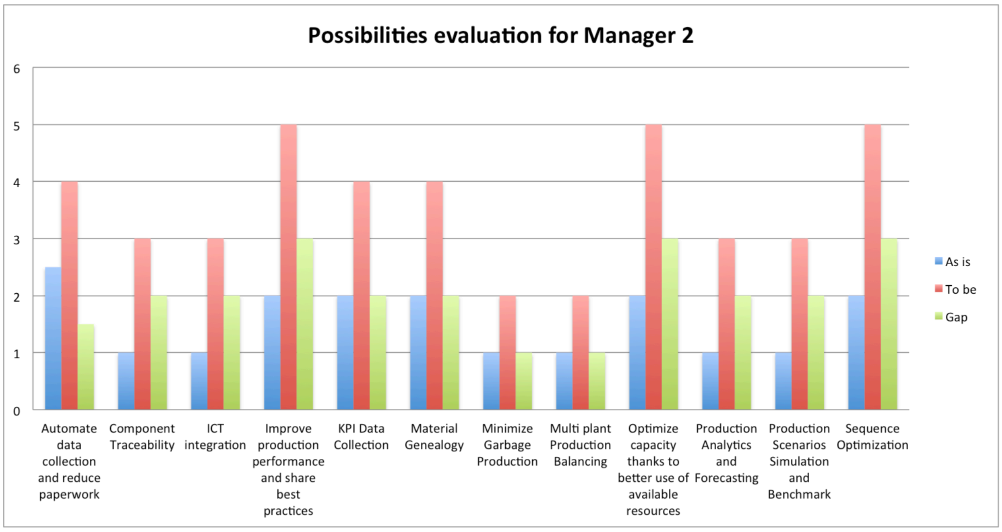

Figure 14 Possibilities' evaluation for Manager 2

To summarize, strengths and opportunities are depicted in the list below:

- Strengths:
  - Attention to detail and quality of the products;
  - Dynamic company;
  - Top-class products and brands.
- Opportunities:
  - Data should be available for an integrated quality system, which can react in real-time and make root-cause analysis;
  - Operations should be supported by better integration of all existing ICT tools;
  - Scheduling is not yet adequately supported by ICT tools;
  - Production process needs to be re-engineered in order to improve the flexibility of production changes and variations.

In analysing the answers given by the company, it is possible to detect its focus and interest in digital transformation and flexible production.

Some activities need to be optimized as in the case of converting a paper process to a semi automated one, which should enable more people to benefit from reliable knowledge and expertise within the company (at the moment "know-how" is restricted to a very small group of people).

Data is well structured, but a more consistent integration should guarantee better collection, management and publishing of data, which should in turn improve standardization. This could create several benefits including defect identification, production and quality reporting, claims and exception management.

Quality procedures should be standardized, taking into account the plant differences. Quality is the most important company objective.

Improvement in sequence optimization and scheduling management will help the company to increase its flexibility towards suppliers and customers. Main benefits could be obtained in the foundry.

Material/Component consumption needs to be monitored and traced both manually and automatically. Managers highlighted that a system, which automatically updates the relevant inventory and provides information to different entities, is necessary.

The system should also update the product genealogy enabling past and future reports.

Finally there is the need to have an integrated logistic system among assembly, and foundry business process areas.

We can say that the company is firmly focused on the digital transformation of its processes, such as the integration of ICT and data analytic tools in order to help make tactical and strategic business decisions. Furthermore, it shows a great interest in flexible and reconfigurable systems related to the issue of production configurations and varying volume, while interest in sustainability is growing within company highlighted by the trend "Environmental awareness" and the possibility of "Planet foot-print and waste reduction".

3.2.2 Case 2: A white goods company

The second case study involved a multinational manufacturer of white goods, its products are manufactured, distributed and sold all around the world and it is the leader in this sector. The company has various industrial plants placed in different countries. In this case study we analyse and interview managers of a production plant situated in Italy. It is the largest production system in Europe both by volume and size, it is composed of two main production processes: i) assembly and ii) fabrication.

In our research, we focus on this specific company because:

- It has purchased its main competitors;
- Its attention to detail and quality of the products is exceptional;
- It products and brands are first class.

The company's global business locations, based on consumer demands of the regions they serve, help create quality products and diverse brand portfolios.

It influences are broad scale but rely on individual regions to personalize products to meet consumer's needs.

The company is mainly working on the development of high-performance appliances that conserve the earth's resources and help homeowners do the same. It continually monitors the environmental effects of its business, not only by creating products that consume less water and energy, but also by improving its manufacturing and distribution processes, and using materials that minimize the impact on the planet. In addition, it complies with federal laws and regulations requiring disclosure of the use of conflict minerals. The most energy the product uses is during its life in the consumers' home, for this reason the company has a long history in environmental conservation. Furthermore 90% of appliances are recycled, according to the Steel recycling institute. The recycled materials can be used to make other products such as furniture, food containers and playground equipment instead of being sent to landfills. The company has also pioneered efforts to safely dispose of ozone-depleting refrigerants. Finally the company is also involved in circular economy whereby it can re-use materials from its products at end of life.

A semi-structured questionnaire (based on the Value Modeler methodology) was submitted to the company.

Starting with the company answers, it is possible to see a substantial correlation in the managers' responses, the main trends are (Figure 15):

- Accelerated use of new technology;
- Extended product variety;
- Environmental awareness.

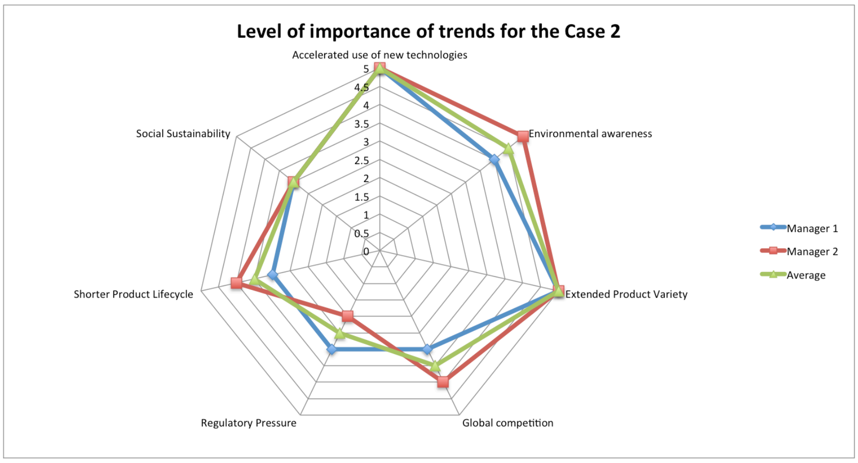

Figure 15 Trends' assessment

It is possible to categorize these contents with the following statements which describes the implications for the company (Figure 16):

- *Adoption of a global and standard solution and homogeneous KPI:* the scope is to define and capture standard factory KPI, and monitor the efficiency of the single workstation;
- *Improve flexibility and harmonizing production landscape across plants:* sequencing of daily production, in order to be more competitive in the global market;
- *Planet footprint and waste reduction:* involving monitoring and optimizing the energy consumption for factory/line/device;
- *Process traceability:* traceability of components and finished goods.

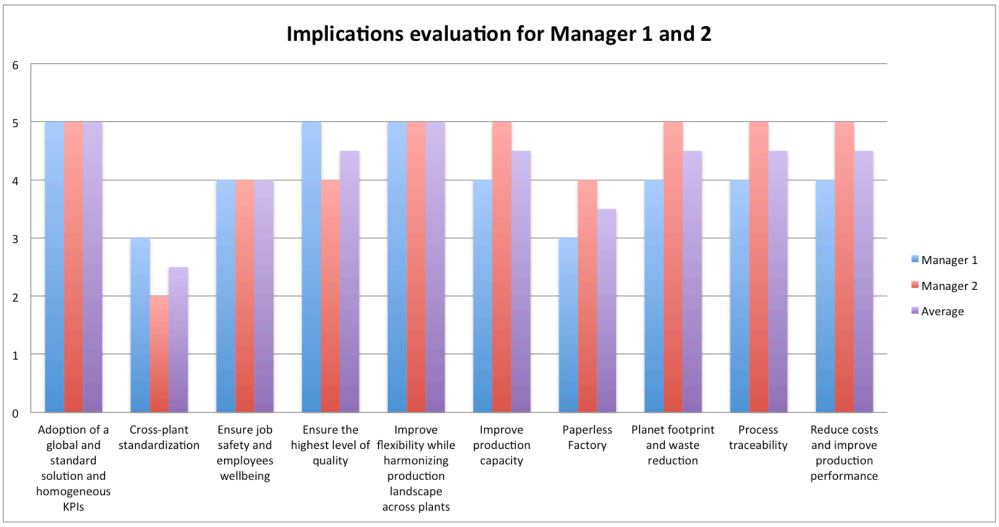

Figure 16 Implications' assessment

We have analysed which internal activities or processes need interventions, defined by the current and the target state of the company. The possibilities addressed by managers can be grouped in three clusters (Figure 17 and 18):

- *"Automate data collection and reduce paperwork":* Data collection needs to be improved to enable a more supportive reporting of activities;

- *"Improve production performance and share best practices"* and *"KPI Data collection":* Need to understand the set of the most useful KPI to monitor production, while the assembly phase is evaluated by yield in a fully automated way, fabrication phase's efficiency is not constantly monitored;
- *"Optimize capacity thanks to better use of available resources"* and *"Sequence optimization":* Challenges of continuously adapting their production targets to variable demand requirements due to the frequent introduction of new models and different departments are not integrated by a unique scheduling plan.

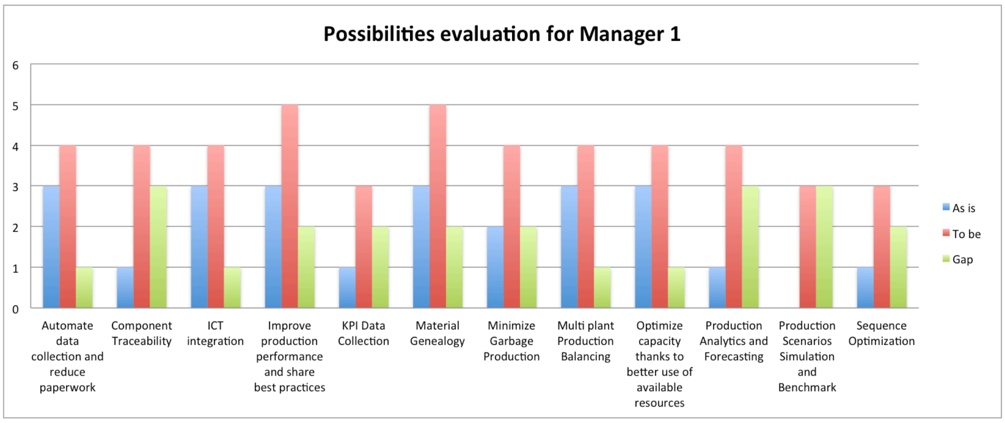

Figure 17 Possibilities' evaluation for Manager 1

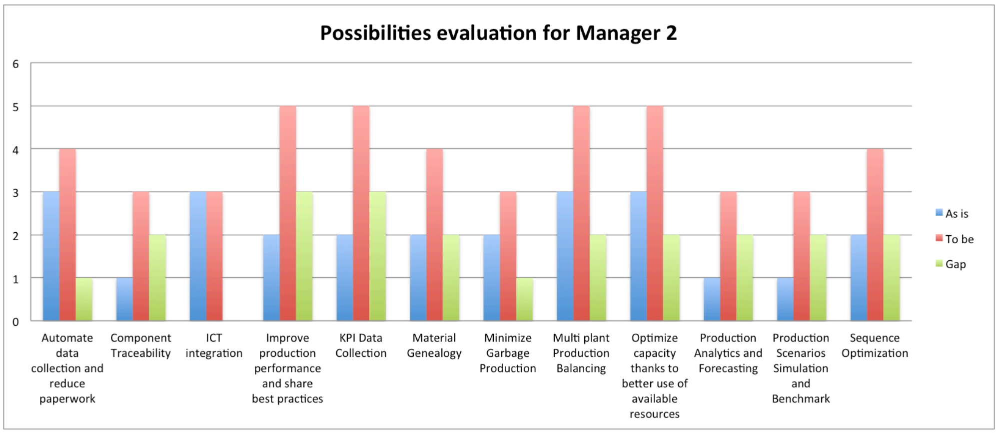

Figure 18 Possibilities' evaluation for Manager 2

To summarize, strengths and opportunities are depicted in the list below:

- Strengths
  - Attention to detail and quality of the products;
  - Enhancement of performance;
  - Extended adoption of Lean principles.
- Opportunities
  - Standard and flexible production;
  - Scheduling is not yet adequately supported;
  - Improve customer education with respect to sustainability;
  - A broader picture in terms of sustainability performance is targeted.

In analysing the answers given by the company, it is possible to detect its focus and interest in environmental performance and flexible production.

The company, on the one hand, would be able to analyse each element of its strategy and business model in order to understand what factors influence sustainability [7,8]. Raw material availability, regulations, waste, climate change and human rights would all be measured using the correct KPIs to calculate their impacts. Additionally, a complete picture of the environmental impact and sustainability requires numerous metrics [11], so the first step for the company in order to measure sustainability is to identify the critical and relevant points of the its business and then define the improvements goals.

Reverse logistics is another relevant topic for the company. It is that branch of logistics that allows going back to the production chain of a product or system in order to "recover value." The company would be able to recover its products in order to return value derived from its obsolete products.

The importance of reverse logistics has grown, due to not only environmental issues and regulations, but also becoming a need for improving strategy and business.

The reasons for implementing reverse logistics by the company are many and can be summarized in the following list:

- Create new sales space;
- Tool for increase competition;
- Protect its profits;
- Disposal legal issues;
- Recover valuable goods;
- Recover value from returns and products at end-of-life.

On the other hand the company shows a great interest in flexible and reconfigurable production systems related to the issue of production configurations and varying volume, particularly it focuses on capabilities that enables the system to easily exchange manufacturing technologies when singular events, such as delayed delivery of supplied parts, or the failure of production equipment could quickly disrupt the production of an entire day. Significant savings potential can be achieved by self-reconfiguration and self-adaptation of production equipment and production workflows during production either based on the CPPS's and work pieces' own state or triggered by information from factory-level systems and external systems.

3.2.3 Case 3: A food company

The third case study concerns one of the main Italian food manufacturers. Its products are produced, distributed and sold around the world and it is the Italian leader in this sector. It is an international group with sales in more than 100 countries. The company has 42 production sites, 14 in Italy and 28 abroad, which produce more than 1,800,000 tons of food products every year.

A world leader in pasta and ready to use sauces in continental Europe, bakery products in Italy and crisp bread in Scandinavia, the products are recognized worldwide as firm family favourites.

The company has various industrial plants placed in different countries. In this case study we looked into a production plant situated in Italy.

In our research, we focus on this specific company because:

- It is the leader in the Italian market;
- It has a large global market share;

- Seeks continuous improvements;
- It has an excellent record in safety and quality of the products.

The food chain involves many steps before the product arrives on the supermarket shelf, and the company plays an important role along this path. The group has stringent controls throughout the supply chain: from the purchasing of raw materials to the production processes, and from the monitoring of products on sale to the development of an effective system of traceability and quality control.

To adapt better to local situations and regulatory constrains, the company has adopted an operating structure divided into four areas: i) Italy, ii) Europe, iii) America and iv) Asia, Africa and Australia.

With this perspective, the company believes it can accelerate its response to the needs of each particular market and use all its synergies more widely, reinforcing the group's position in the global market.

The company has two main objectives. The first is to satisfy consumers taste. Quality and nutrition are an absolute must, and are always motivated by the desire to create new flavours and recipes. Its work in food safety, nutrition, environmental sustainability and people's wellbeing is far reaching, and this pushes the company to design new business models. This leads to the second objective, which is to increase revenue while continuing to reduce the impact on the planet and promote healthy eating habits.

The company's processes have been re-engineered to be as energy efficient as possible while also reducing fossil fuels to a minimum.

A semi-structured questionnaire (based on the Value Modeler methodology) was submitted to the company. Starting with the company answers, it is possible to see a substantial correlation in the managers' responses, the main trends are (Figure 19):

- Environmental sustainability;
- Digitalization;
- Market competitiveness.

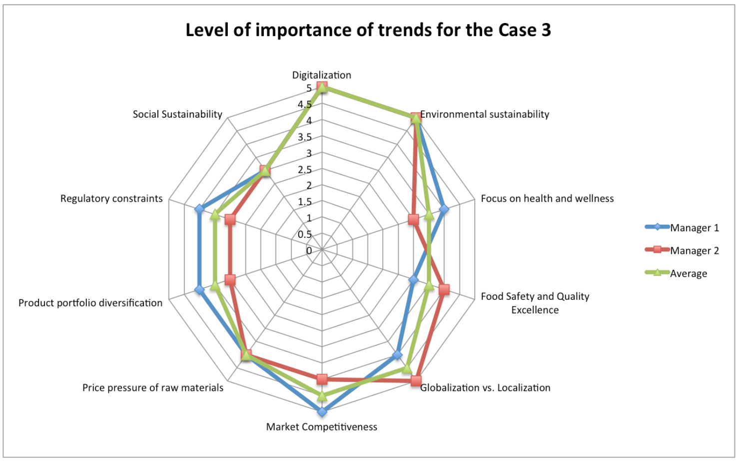

Figure 19 Trends' assessment

It is possible to categorize these contents from the following statements, which describe the implications for the company (Figure 20):

- *Ensure the highest level of quality:* the rapid development of technology, combined with increased global competition and more stringent customer demands puts pressure on the company to continually improve the quality of its products and processes;

- *Improve flexibility and harmonizing production landscape across plants:* it has been shown that more flexibility in the workplace and a results-based approach can increase productivity and, at the same time, contribute to creating a more inclusive working environment, allowing everyone to manage their own jobs differently. For this reason, the company would implement a project, offering employees the possibility of more autonomy on how, where and when they work, determining and adapting their working methods according to personal and corporate requirements.
- *Planet footprint and waste reduction:* the company is fully committed to respecting the environment and human health. The scope is to minimize fossil fuels and reduce palm oil.
- *Reduce costs and improve production performance:* cost of raw materials, energy and water are growing increasingly volatile. The company wants to optimize its sustainability practices in order to be less exposed to these swings;

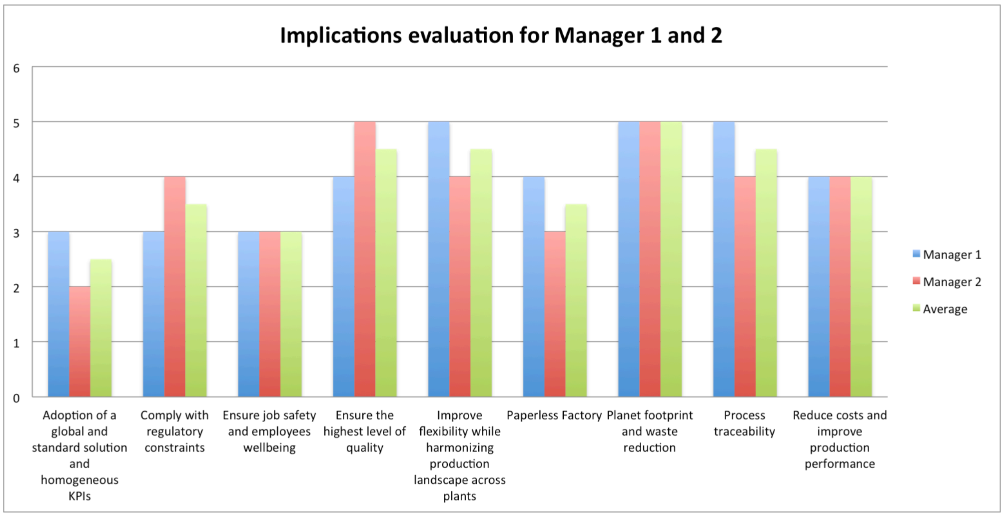

Figure 20 Implications' assessment

We have analysed which internal activities or processes need interventions, defined by the current and the target state of the company. The possibilities addressed by managers can be grouped in three clusters (Figure 21 and 22):

- *"Automate data collection and reduce paperwork":* these technologies could allow monitoring quality, efficiency and traceability. The technology could be used to provide consumers with a guarantee of a product's environmental credentials.
- *"Improve production performance and share best practices" and "Optimize capacity thanks to better use of available resources":* on the one hand the company would introduce tools and technologies in order to use resources in a more environmentally responsible manner, by improving their sourcing decisions, and implementing circular-economy solutions in the food chain. While on the other hand the goal is to overcome supply seasonality and demand, improving flexibility.
- *"Minimize garbage production":* Sustainability is a high priority for the company and food waste is a problem that attracts significant attention. This problem could be mainly caused by: i) improper storage, ii) overproduction, iii) improper sales or demand forecasts and iv) faults and breakdowns. This

results in a continuous need to re-engineer the production processes and therefore requires more flexibility on the shop floor.

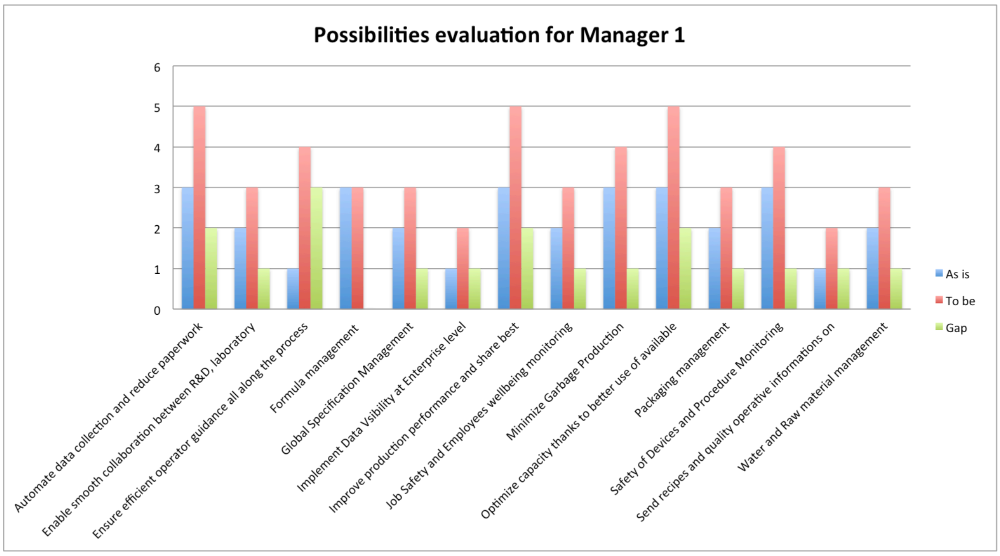

Figure 21 Possibilities' evaluation for the Manager 1

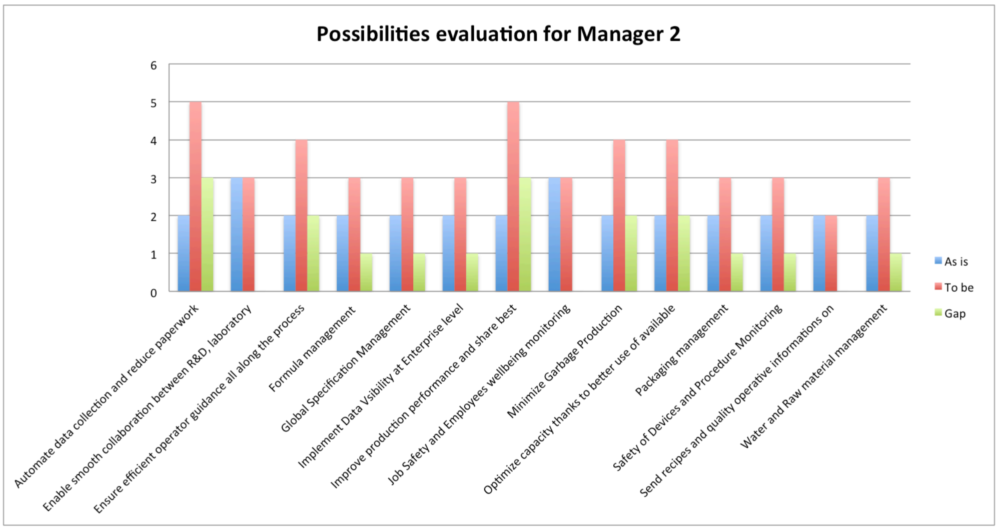

Figure 22 Possibilities' evaluation for Manager 2

To summarize, strengths and opportunities are depicted in the list below:

- Strengths
  - Attention to detail and quality of the products;
  - Excellent record in safety and quality of the products;
  - Dynamic company.
- Opportunities
  - Standard and flexible production;
  - Waste reduction;
  - Improve customer education with respect to sustainability;

In analysing the answers given by the company, it is possible to detect its focus and interest in environmental competitiveness and digital transformation. We can see that its objective is to digitalize its design and manufacturing processes in order to improve value and increase competitiveness in the market. To achieve this, two main factors have been detected: “Planet footprint and waste reduction” and “Reduce costs and improve production performance”.

Data analytics can help the company use resources in a more environmentally responsible manner, improve their sourcing decisions, and implement circular-economy solutions in the food chain. These technologies would allow the monitoring of quality, efficiency and traceability. It would be possible to trace a food product back along its entire chain of production, from supermarket shelf to farmer’s field. From the company’s point of view, competitiveness depends mostly on the sustainable factor both from the planet footprint and the waste reduction, keeping in mind the lean thinking principles.

The company faces fluctuations in demand as it feels the need to keep a safety stock to maintain a high level of service and satisfy customer needs. Both have a negative impact on food waste. Reducing this uncertainty and improving flexibility can create benefits for the company. It means lower inventory costs and an ability to plan production better, fresher products, less waste, and better in-stock position, resulting in higher margins and more sales, and for the consumer, the product is fresher and keeps longer.

3.2.4 Case 4: A soft drink company

The case study concerns a syrup producer and bottling company. It is a leader in the bottling process in Italy, it has 4 plants and more than 20 production lines. The company covers one third of the Italian market, it mainly produces and bottles carbonated and non-carbonated drinks, diet drinks and bottled water. The soft drinks industry is a very competitive sector, characterised by numerous smaller companies and dominated by few multinationals. Its consumption has increased substantially over the last 50 years. Moreover, its demand has shifted due to changes in consumers' behaviours.

The interviews with SC Manager of the company, allows us to describe the structure of the company, which is composed by four different plants:

- Plant 1: produces and bottles carbonated and non-carbonated soft drinks in PET, glass, cans, Pre-Mix and Bag-in-Box;
- Plant 2: produces and bottles carbonated and non-carbonated soft drinks in PET, Pre-Mix and Bag-in-Box;
- Plant 3: produces and bottles carbonated and non-carbonated soft drinks in PET, glass and cans;
- Plant 4: produces and bottles water in PET.

In our research, we focus on this specific company because:

- It is a leader in the bottling process in Italy;
- It has a great attention to safety and quality of the products;
- It presents a great focus on customer.

Packaging is a critical and relevant aspect of the company; it represents a huge part of the whole wastes production.

It is a fundamental means for protecting and preserving the beverage properties. On the one hand the company needs to control its weight to reduce environmental impact, on the other hand has to use the correct quantities needed in order to extend the products’ life and therefore reduce the probability that beverages could not be consumed. Another very relevant aspect for the company is packaging design. Currently the trend of mass personalization is also covering the beverage sector. There is an increased demand for personalized products in terms of individualized packaging such as the possibility to have one's own name on it. Therefore, packaging remains a huge issue, where the company needs to arrive at a balance between customer demands versus product protection versus sustainability.

An additional aim of the company is to minimize water consumption; in fact facing the increasing global water crisis, it is fundamental for it to preserve this valuable resource and adopt strategies for its efficient consumption. The water crisis is defined as the greatest threat that our planet will face, from the arid agricultural areas to the possibility of millions of people having no access to water. In this context, the company has carried out huge investments in the development of technologies and processes, which allow the reduction of water requirements and permit efficient recycling of wastewater. Treated water can be desalinated, and organic products can be removed with the aim of fulfilling conditions of water reapplications.

A schedule with semi-structured interviews (based on the Value Modeler methodology) was submitted to the company.

Starting with the company answers, it is possible to see a substantial correlation in the managers' responses, the main trends are (Figure 23):

- Environmental sustainability;
- Digitalization;
- Price pressure of raw materials.

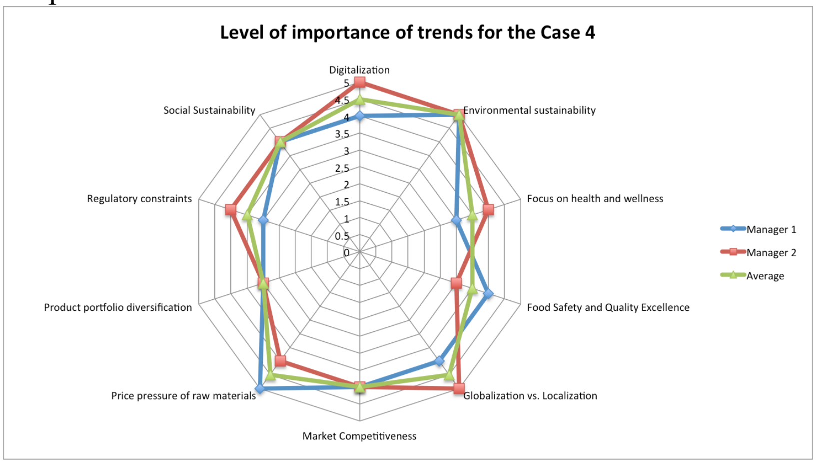

Figure 23 Trends' assessment

It is possible to categorize these contents from the following statements, which describe the implications for the company (Figure 24):

- *Ensure the highest level of quality:* this is a primary topic of the company, it embraces the quality of: i) control standards, ii) water supply, iii) product and iv) packaging.
- *Improve flexibility and harmonizing production landscape across plants:* the company requires production lines that are flexible and smart, without compromising on quality, speed and efficiency. These solutions allow for optimized production uptime, reduced resource consumption and minimize machine set-up times, while keeping the Overall Equipment Efficiency (OEE) consistent.
- *Planet footprint and waste reduction:* the company is focused on delivering sustainable long-term growth while leaving a positive impact on society and the environment. The goal is to re-think its product portfolio offering healthier options and makes drinks more sustainable.

- *Reduce costs and improve production performance:* the company recognise that waste represents a cost and are committed to reduce its generation wherever possible. Furthermore, with expensive raw material costs and high volumes, the company needs to improve performance over time and under harsh conditions.

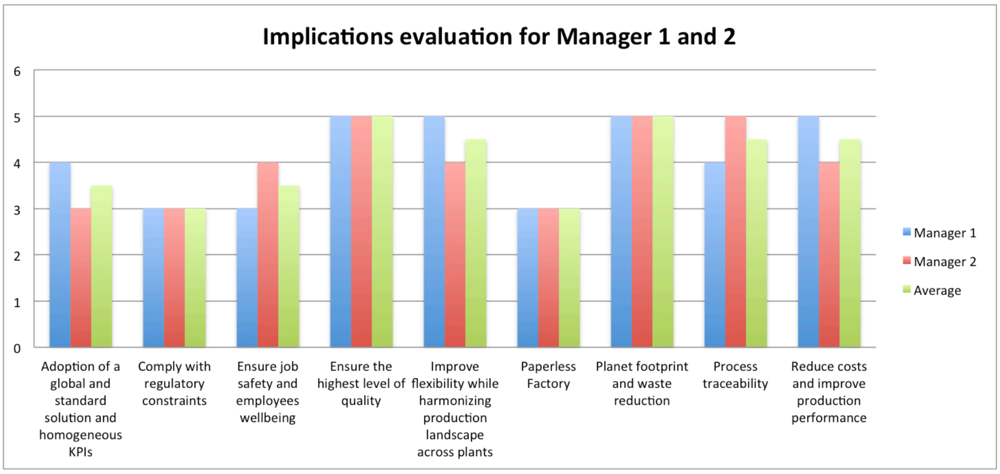

Figure 24 Implications' assessment

We have analysed which internal activities or processes need interventions, defined by the current and the target state of the company. The possibilities addressed by managers can be grouped in three clusters (Figure 25 and 26):

- *"Minimize garbage production":* In order to reduce the environmental impact of its packaging, the company re-design bottles in order to reduce their weight and therefore wastes.
- *"Packaging management":* The design of packaging aims at reducing, recycling and reusing materials for the safety of natural resources. The company considers packaging as one of the main objective of its environmental management; in fact it pays close attention both to the design of the packages, and their recovery.
- *"Send recipes and quality operative information":* the goal is to develop smart products, which maintain information about their Recipe and Bill of process (BOP). The materials of the products' recipe use this information to steer their own production and step-wise transformation towards concrete product instances or product batches.
- *"Water and raw materials management":* Water is used to produce drinks, clean and prepare bottles and for cooling and cleaning equipment. In this direction, the primary objectives of the company are: i) efficiency in water consumption and ii) return to nature the water used in the production of beverages.

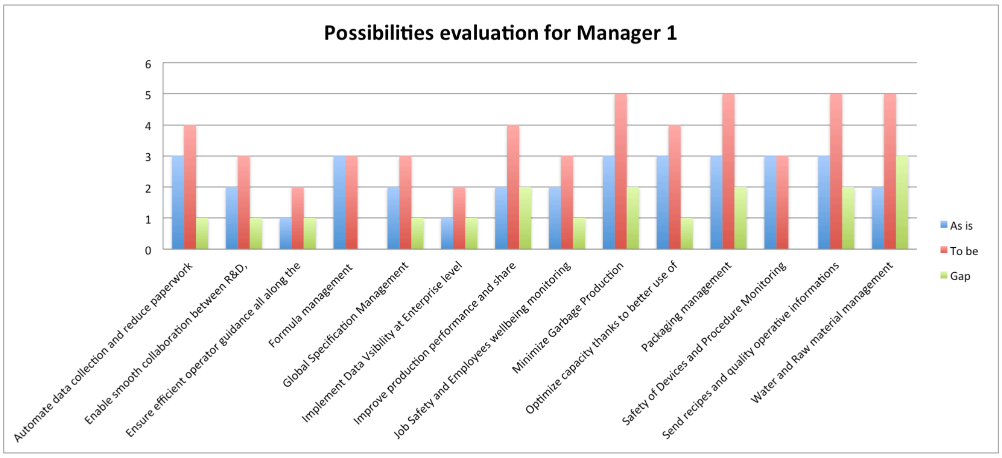

Figure 25 Possibilities' evaluation for Manager 1

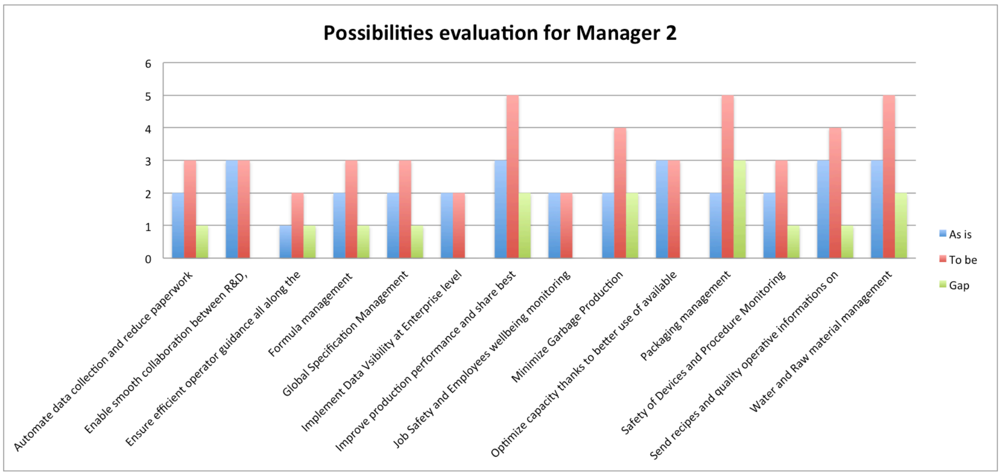

Figure 26 Possibilities' evaluation for Manager 2

To summarize, strengths and opportunities are depicted in the list below:

- Strengths
  - Attention to detail and quality of the products;
  - Great focus on customer;
  - Inclination to innovation and digitalization.
- Opportunities
  - Standard and flexible production;
  - Digital transformation;
  - Water consumption reduction;

In analysing the answers given by the company interviewed, it is possible to detect its particular focus and interest on sustainable topics such as packaging and water consumption and routing flexibility. Concerning packaging, the design of it aims at reducing, recycling and reusing materials for the safety of natural resources. The company considers packaging as one of the main objective of its environmental management; in fact it pays close attention both to the design of the packages, and their recovery.

Some activities should be started in order to make consumers take an active part:

- Returnable packaging: which allows recovery bottles and sensitizing consumers and make them more aware of choosing a sustainable product;

- Post consumer actions: a special machine has been developed, it allows compacting bottles and cans with the scope of recovery them and incentivise customers through discounts.

Managers illustrate that packaging is a milestone of the company in fact all operations are made in the weight reduction of packaging. Furthermore, packaging recovery and glass recycling actions have been embraced. Concerning packaging recovery, it allows reducing its impact on the society and managing waste. While glass recycling permits the company to reuse it in all operations; in fact the recovered bottles are processed, washed and are re-inserted in the production line. Discarded bottles, which then don't achieve quality requirements, are sent to the ecological islands of each plant to be conditioned and sent to recycling plants.

On the other hand with respect to water issues, a system of capturing and storing rainwater has been developed, it allows to re-use water for auxiliary services such as fire protection and sanitary services of the plants. The company also implements a system of cleaning with the aim of reducing energy and water consumption. The huge water consumption both for the production and the cleaning processes needs an accurate management both for economic and environmental purposes.

Finally, set-up times, cleaning times and routing flexibility emerged as critical factors too.

Concerning the primary phase, managers highlight that there is the possibility to produce different recipe in different time with the same line (mixer), or produce different recipe based on the same ingredients in sequence, but it is necessary to consider that after a production cycle, the line needs to be cleaned and re-organized.

While the secondary phase mainly addresses the issue of routing flexibility. Managers explained that an increased on routing flexibility is needed in order to interchange the order in which the required manufacturing operations are performed due to congestion, breakdowns and blocking.

3.2.5 Flexibility model (RQ 2)

The case studies have proved the strategic importance of sustainability and flexibility as competitive dimensions, which create and deliver value for companies.

Concerning flexibility, thanks to the strategic vision and operational support of Siemens MES, we have decided to investigate this issue more thoroughly.

The scope was to create a model that provides a structural definition of existing flexibility types in line with the heterogeneity of the topic and their composition, as well as providing decision support regarding the identification of the correct flexibility demand of any given manufacturing scenario. This was a joint venture with the University of Nuremberg due to its inclination to i) automation technology and ii) digital transformation.

All works related to this context are in two domains: i) flexibility and ii) value modelling in manufacturing systems. Both domains are crucial, the research in flexibility is important for the creation of the underlying flexibility model, while the research in manufacturing value modelling is seen as key in constructing the framework for identifying the correct flexibility demand for any scenario.

Flexibility in manufacturing systems is not a completely new trend and therefore many different approaches exist that try to give an overview about the different types of flexibility definitions as well as the drivers for flexibility itself [13], [83]–[85]

Most of these approaches have the same flexibility model by Sethi and Sethi in common [47], [86]. In this context the aim is not to introduce a completely new flexibility model, but instead the goal is to use a well-established model and to analyse the necessary adaptions needed with regard to the current challenges in manufacturing.

Similar to the previous approaches the flexibility model also uses the model from Sethi & Sethi (1990) for representing the hierarchical composition of different flexibility types. Figure 27 presents an overview of this flexibility model. In their work Sethi & Sethi present a hierarchical model consisting of eleven types of flexibility, which are either affecting the important components of the system and the product (machine, material handling, operations) or the system as a whole.

However the work of Sethi and Sethi mainly refers to the work of Browne et al., who present a similar hierarchical structure for flexibility types that also includes most of the types mentioned by Sethi and Sethi.

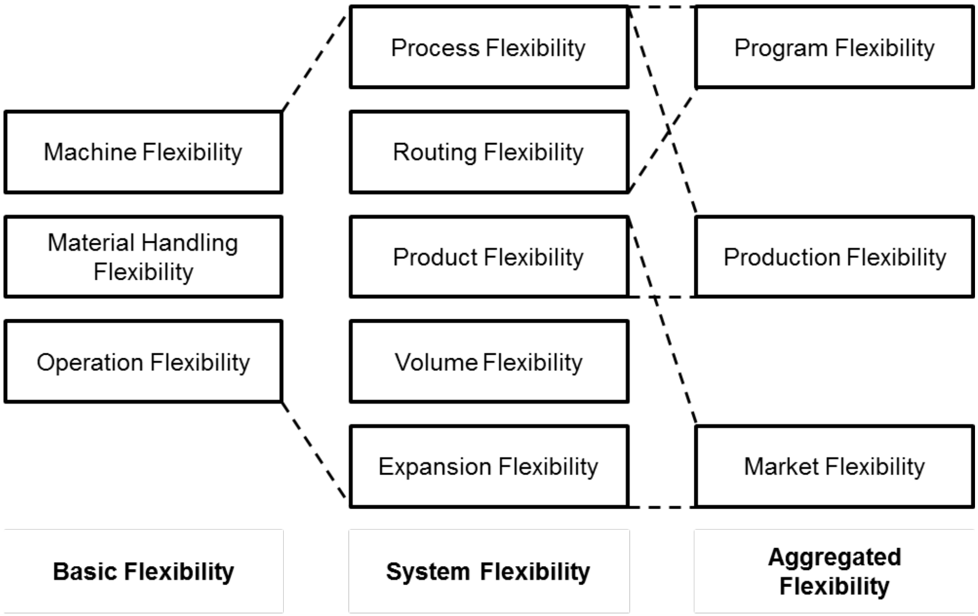

Figure 27: Flexibility Model of Sethi and Sethi (per Sethi & Sethi, 1990)

Furthermore, another author also analyses flexibility in the domain of flexible and reconfigurable manufacturing systems, where most of the flexibility types from Browne as well as Sethi and Sethi are used again [83]. Besides this classification there are also authors that focus mainly on the trigger of flexibility.

Kara and Kayis for instance investigate the origin of flexibility demand and state that it can either occur externally from a market point of view or internally from a manufacturing process view [48]. Furthermore they also create a mapping between the causes for flexibility demand and flexibility types that can be used to handle them. Their results are also shown in Table 7.

In recent research, Oke (2005) proposed a framework for analysing two specific types of flexibility: volume and mix-based. Thanks to this framework, Oke is able to analyse source factors of the two aforementioned types of flexibility [87].

Mishra *et al.* (2014) developed a conceptual framework for flexibility assessment that describes linkages between three relevant elements of flexibility, which are i) drivers, ii) enablers and iii) outcomes [88].

Fischer *et al.* (2015), defined a framework, which differentiates between various levels of flexibility and gives companies directions and guidance in analysing their processes [89]. The framework is composed of five dimensions: level 1 no flexibility, level 2 Intrafirm flexibility, level 3 Reactive flexibility, level 4 Proactive flexibility and level 5 Paradigmatic flexibility [89].

Table 7: Flexibility demand causes and flexibility types (according to Kara & Kayis, 2004)

Flexibility Demand Causes		Flexibility types
Market View	Variability of demand	Volume flexibility; Expansion flexibility; Labor flexibility, Control flexibility
	Shorter life cycles (technologies / products)	Control Flexibility; Product flexibility, Machine flexibility; Process flexibility; Material handling flexibility; Operation flexibility; Labor flexibility; Control flexibility
	Shorter delivery times	Delivery flexibility; Machine flexibility; Labor flexibility, Routing flexibility
	Product diversity	Product flexibility; Labor flexibility; Mix/production flexibility; Machine flexibility; Material handling flexibility; Operation flexibility; Labor flexibility
Manufacturing process view	Machine downtime	Routing flexibility; Operation flexibility; Buffer; Control
	Material input	Machine flexibility; Material input flexibility; Control
	Variation in workforce	Labor flexibility; Control flexibility

Reviewing the different flexibility models it becomes clear that a connection between general market trends and the demand for a specific flexibility type can be drawn. In order to support the decision towards a specific flexibility type it is not enough to simply just classify them. Browne et al., as well as Sethi and Sethi already mention a hierarchical structure, with the potential of providing some degree of decision support, since higher level flexibilities consist of a certain set of lower level flexibilities (Browne et al., 1984; Sethi & Sethi, 1990). Kara and Kayis on the other hand take a different approach, ignoring the hierarchical structure, instead the authors present a model with a mapping of internal and external triggers for flexibility demand with different flexibility types (Kara & Kayis, 2004).

The flexibility model now combines the two perspectives by holding on to the hierarchical structure as well as respecting internal and external factors (compare to Browne et al., 1984; Kara & Kayis, 2004; Sethi & Sethi, 1990). This combination now also leads to further review considering evaluation regarding the relationships between internal and external factors.

In connection with the background of flexibility and value modelling the flexibility model aims at providing a structural definition of existing flexibility types and there composition as well as the providing decision support regarding the identification of the correct flexibility demand of any given manufacturing scenario.

The general overview of possible flexibility types in manufacturing systems is part of the flexibility model and can therefore be used for every production scenario. The second part, the identification of the required flexibility demand however requires information, which depends on the scenario under study.

It is mandatory to capture the environment of the given scenario by identifying the external and internal influence factors. Furthermore it is also important to provide a general view regarding the existing flexibility types that can occur in a manufacturing setup.

Finally a mapping between the internal and external influence factors as well as the flexibility types has to be created in order to highlight, which flexibility type might be suitable for handling the given set of internal and external influence factors.

3.2.5.1 Components of the flexibility model

The flexibility model uses the structure of external influence factors (Trend), internal influence factors (Implication), functional areas (Possibility) from MVMM [90] as components and introduces the flexibility type as a new element for presenting different flexibility manifestations in manufacturing that have an impact on the complete system.

External influence factors

The external view represents the trends. This component describes the specific environment in which a company operates. Examples for current trends in manufacturing could be the complexity of supply chains due to decreasing lot sizes and increasing customization [11] .

However, the trends can vary from industry to industry and leading to industry specific libraries for presenting the possible trends. Nonetheless there are global categories, which apply to each industry.

In alignment with Kara and Kayis this categories are the demand, the product lifecycle and the variant spectrum. Each trend can be assigned to at least one of those market related categories.

Internal influence factors

The external view is followed by the analysis of the internal process and strategies. Therefore, the implication section of MVMM is used to represent the internal influence factors including the goals and strategies of the manufacturing company. In general the flexibility model aims at aligning the internal influence factors according to the dimensions of the iron triangle: performance/quality, time/schedule and cost [91].

Different internal influence factors can be derived from Porter´s generic strategies of differentiation, cost leadership and focus [92]. In this case, the differentiation strategy fits to the performance dimension, meaning that the most important indicator for differentiation is the performance, which could lead to higher costs. When a cost leadership strategy is favoured, the focus should be on the cost constraints while having fewer requirements regarding the performance.

However the specific sets of possible strategies can again vary from scenario to scenario, leading to industry specific contents that contain all possible influence factors.

Nonetheless the previously introduced structure is remaining the same and these influence factors should be formulated as cost, performance and time requirements.

Functional area

The functional area defines the position within a primary activity of the value chain. Functional areas can therefore be listed for inbound logistics, operation, outbound logistics, sales and marketing as well as servicing. Since this work deals with manufacturing systems, the functional area is limited to the Manufacturing Operation Management

(MOM) domain. However, Table 8 presents the possible elements from ISA 95 that represents the functional areas of the flexibility model.

Table 8: Functional area overview

Functional area	Description
Production operation management	Production Operations Management refers to the application of management principles to the production function in a factory, it involves application of planning, organizing, directing and controlling the production process.
Maintenance operation management	Maintenance Operations Management is defined as all the activities of the management that determine the maintenance objectives or priorities, strategies and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, and several improving the methods including economical aspects in the organization.
Quality operations management	Quality management needed to maintain a desired level of excellence. This includes creating and implementing quality planning and assurance, as well as quality control and quality improvement.
Inventory operations management	Inventory management is the overseeing and controlling of the ordering, storage and use of components that a company will use in the production of the items it will sell as well as the overseeing and controlling of quantities of finished products for sale.

The last item of the flexibility model framework is now the flexibility type. Based on the pervious analysis of internal and external and internal influence factors and the scope definition through the selection of the functional areas the next step is to evaluate the flexibility types of manufacturing systems in order to select the flexibility type that fits to the results from the previous analysis.

However, before understanding this part of the model it is mandatory to understand the underlying flexibility model of the framework.

Flexibility types

The last component is the flexibility type component that represents the novel flexibility model of the flexibility model. Four flexibility types with an impact on system level are identified: variant spectrum, volume, expansion and scheduling (Table 9). The selection of these types is derived from the performed literature review and represents the consolidation of the analyzed flexibility types and their definitions.

The first flexibility type, variant spectrum, is mainly derived from both the process and product flexibility from Sethi and Sethi and therefore it does not only aim at the flexibility to produce similar parts but also new parts within a production line without the requiring major setup effort. Hence the term variant spectrum is used to describe the outcome of different items that can be produced by a production line. Those items can be different variants of the same product or even different products.

The expansion flexibility on the other hand side focuses more on the trend of plug and produce, since it is described as the flexibility that enables the system to easily exchange capabilities in terms of manufacturing technologies [47]. Considering the previous flexibility types this could also be connected to the variant spectrum flexibility in cases were new technologies are needed to extent the current variant spectrum.

Another flexibility type is the scheduling flexibility, which is tightly connected to prioritization and delivery time as well as efficiency and utilization optimization topics. It partly includes the delivery flexibility that Oke defines as “the ability to change planned or assumed delivery dates [87]”. However, scheduling flexibility in the connection with the flexibility model is not just limited to the use case of delivery time topics. As mentioned before the flexibility regarding the adaption of production plans can also be used to enhance the overall utilization of the system as well as the optimization regarding other measures such as cost efficiency. An example for that would be the scheduling of production tasks that require an high-energy consumptions at times where the energy costs are lower. This could be beneficial if there are different prices between day and night.

The last flexibility type deals with the volume. This flexibility characterizes a system, which is capable of producing efficiently even though the output can vary between different levels. In contrast to the variant spectrum flexibility, this flexibility type considers the quantity of each good that can be produced in the system. However, in areas where different production mix solutions are compared or evaluated both types of flexibilities have to be analysed together because the quantity of each item in the variant spectrum could vary.

As mentioned earlier the flexibility model follows the hierarchical structure from Sethi and Sethi and therefore each flexibility type consists of the same set of flexibility building blocks.

Table 9 Flexibility types

Flexibility type	Characteristics	Sources
Variant spectrum	Amount of different final products that can be produced by a manufacturing system, compared to the required effort (operational and invest)	[93]; [94]; [85]; [88]; [95]; [96]; [97]; [98]; [99]; [100]; [101]; [11]; [102]; [103]; [104]; [105]; [106]; [83]; [87]; [107]; [48]; [108]; [109]; [110]; [111]; [112]; [84]; [113]; [114]; [115]; [47]
Expansion	Capability to arrange production mix and production order in different ways compared to required effort (operational and invest)	[93]; [85]; [99]; [105]; [83]; [48]; [109]; [111]; [112]; [84]; [113]; [115]; [47]
Scheduling	Output range in which the manufacturing system can be operated profitably, compared to required effort (operational and invest)	[93]; [85]; [88]; [116]; [117]; [97]; [118]; [103]; [105]; [83]; [87]; [107]; [48]; [109]; [111]; [112]; [84]; [113]; [114]; [47]
Volume	Amount of additional manufacturing capabilities that can be added to the manufacturing system, compared to required effort (operational and invest)	[93]; [85]; [88]; [97]; [98]; [99]; [118]; [100]; [101]; [11]; [102]; [103]; [105]; [106]; [83]; [87]; [107]; [48]; [119]; [109]; [111]; [112]; [84]; [113]; [47]

Those building blocks are the workstation flexibility, the transport flexibility, the flow control flexibility as well as the flexibility provided by the ICT system. Each of the four system level flexibility types can be realized with different characterizations of the system components (Figure 28). However, the concrete flexibility of those components strongly depends on the given scenario. On the one hand side, variant spectrum flexibility could be realized with a set of highly flexible workstation connected through a rigid transport system. But it might also be possible to reach the same flexibility with less flexible workstations that are connected via a more flexible transport system. Additionally, the most flexible machine, transport system or flow control does not provide any improvements if their flexibility potential cannot be processed by the ICT systems that are responsible for planning and executing the manufacturing processes.

Depending on environment and the existing internal influence factors the characterization of each building block can differ. Hence the building blocks are necessary to define the solution template that describes the flexibility demand of the manufacturing system.

Relations in the flexibility model

Besides the general description of the flexibility model, it is mandatory to explain the application of the model itself. Since the general approach is derived from the MVMM approach it is also possible to create relationships between the different components.

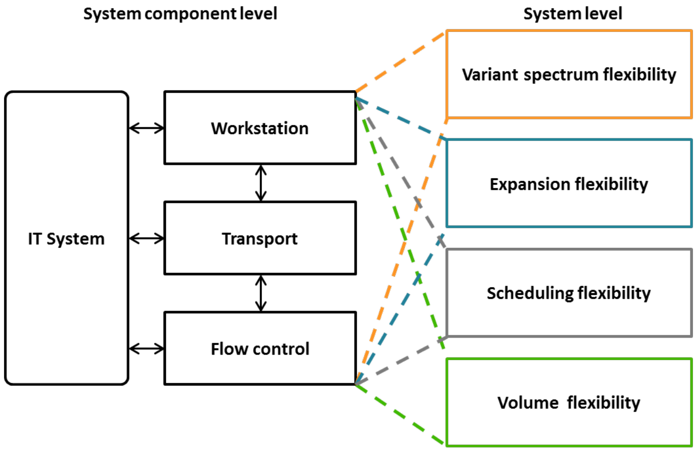

Figure 28: Flexibility demand

As previously stated, the MVMM has three constituting blocks. The first is concerned with the definition of the external impact factors (Trends), which represent the external view. This component describes the specific environment in which company works, Trends are the changes/pressure from the business environment that make necessary a company to go through new ways of managing its business in order to maintain its value.

The second is concerned with the identification of internal impact factors (Implications), which are used to analyse internal process, strategies and goals of the company. Implications allow identifying how the company could respond to external trends.

Finally, the third block concerned "Functional area" which are the essential practices and tools that the company needs in order to positively respond to take advantages of the changes. According to the hierarchical structure of the MVMM it is possible to identify pressure and challenges that have an impact on the company environment. And starting from these trends, define capabilities, relevant practices and tools that are essential for driving companies in the flexibility process improvement.

Therefore, there is the possibility to create a relationship between external influence factors (trends) and the business strategy (internal factor) that is used to tackle them. This means there is a certain set of internal influence factors that fit to a certain external factor.

Continuing with this approach the MVMM also defines a relationship between the internal factors and the functional area. This relationship is used to further specify the solution space by specifying, which internal factor relates to which ISA 95 pillar. With the flexibility model an additional relationship is introduced that shows the relationship between an internal influence factor and a system level flexibility type.

Based on those relationships it is then possible to identify the corresponding flexibility type for a given problem statement consisting of the identified market trend as well as the identified internal actions for dealing with it.

However, since those input factors depend strongly on the different production use cases it is mandatory to create a scenario specific set of external factors (market trends) and internal factors (business strategies) before the relationships to the functional area and the flexibility domain can be created.

3.2.6 How new technologies and capabilities can improve flexibility and sustainability (RQ 2.1)

As mentioned, manufacturing companies are facing continuous increasing pressure for flexible production in terms of variety and options caused by customer demand.

Until now, industries have addressed this pressure by planning assembly lines for a given model and then controlling the production sequences by optimising them with respect to process restrictions and KPIs.

The assembly line, once designed remains essentially unchanged throughout the life cycle of the product. In this way the assembly line with its physically fixed arrangement of production resources strictly determines the intra-logistical processes of the whole production and supply chain.

Despite the obvious advantages of the controllability of this organisation, it would lack the necessary flexibility for smaller series and significantly shorter life cycles of products.

The use of new flexible machines that adapt to the requirements for the part being made is another dimension of Industry 4.0. This achieves a highly flexible, lean, and agile production process enabling a variety of different products to be produced in the same production facility. Profitable mass customization allows the production of small lots due to the ability to rapidly configure machines to adapt to customer-supplied specifications and additive manufacturing.

It is necessary also to optimise the trade-off between sustainability, flexibility, management of the warehouses, stock and transport for the products personalisation.

To support this, new tools and technologies are required for the configuration of corporate networks to favour and promote the composition of adaptive and interoperable enterprise networks that enable cooperation and communication between the various players in the value chain.

With this in mind, CPPS presents the aforementioned characteristics as a highly flexible machine, which adapts to the specific production requirements. CPPS technologies are composed of production units, which are aware of their own production skills, capabilities, state, and their physical and virtual environment. Different production units can be identified such as machines, robots or conveyors.

When connected together, cyber physical product units determine potential production collaborations without explicit engineering or orchestration and perform a Plug&Produce action.

Plug&Produce also allows the bottom-up composition of decentralized, self-organizing CPPS in a modular, fractal manner. Multiple smart production machines are plugged together creating a smart production line and multiple production units achieve a smart process cell. Likewise, multiple smart production lines or process cells are plugged together towards a smart production area, and multiple smart production areas are plugged together to the entire shop floor of decentralized, self-organizing CPPS. The default production behaviour of higher-level elements in this hierarchy is determined with the same Plug&Produce mechanisms that apply when two production machines or production units are connected. Figure 29 shows the composition of CPPS from cyber physical production unit via Plug & Produce.

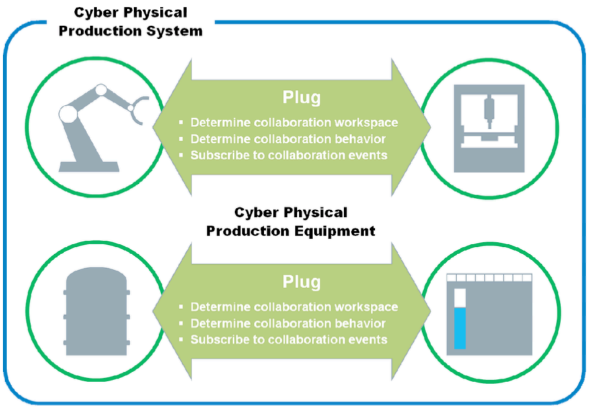

Figure 29 The composition of CPPS from cyber physical production unit via Plug & Produce.

Production processes in the CPPS are self-organized, cooperative, and decentralized, steered by the product instances or batches to be produced. For this purpose, products are smart and maintain information about their bill of material (BOM) / Bill of process (BOP). The materials of the products’ BOM use this information to steer their own production and step-wise transformation towards concrete product instances or product batches.
In cooperation and interaction with the cyber physical production units, materials identify the specific unit that offers the production skills required to execute the next production / processing step in their BOP. Once this unit is determined, they configure transportation unit like smart conveyors or pipes with information to route them to that unit.

The notion of products steering their own production also transfers to continuous production by considering it as the production of a batch with an infinite volume and continuous material replenishment. In a production steered by products, super-ordinate control is needed only in case of exceptional situations and explicit human intervention like emergency shutdown, responses to severe alarms, maintenance and repair of units, and structural changes to the CPPS. All negotiations are supported by advanced IT services like data analytics, simulation, and constraint solving to find an optimal solution under the consideration of all applicable constraints, such as factory or plant-wide KPI, committed production orders, and the current state of the entire CPPS. All entities of the CPPS orchestrate themselves according to the negotiation results: ERP services to manage the production orders and involved assets, the MOM services to plan, manage, and track their execution, and the units to self-organize the actual production of the ordered products.

Decentralism and self-organization in a CPPS thus means that there is no distinguished central entity in the CPPS that has the sole responsibility and authority for the orchestration and execution of production processes. Instead the orchestration and execution of production processes is federatively organized by all relevant entities in the CPPS, under explicit utilization of both local knowledge and skills of units and of factory or plant wide IT like ERP, MOM, data analytics, and simulation.

Starting from the defined flexibility types, the scope of this research question is to understand what technologies could support industrial systems to be more sustainable and flexible.

It is necessary to optimise the trade-off between sustainability and flexibility verses management of the warehouses, stock and transport for the products personalisation.

To support this, new tools and technologies are required for the configuration of corporate networks to favour and promote the composition of new networks that cooperate and communicate between the various players in the value chain.

For each flexibility type (variant spectrum, expansion, scheduling and volume), the scope is to demonstrate the principal contributions expected by using specific cases described in terms of process improvement. The identified flexibility type in manufacturing systems are discussed and compared with the various reconfiguration cases, which include specifically the planning, orchestration, and optimization of production processes within MES. Finally, the cases presented by these manufacturing paradigms are discussed in order to demonstrate how far decentralization and self-organization can be steered to achieving Industry 4.0 key requirements.

The logic behind the research methodology is to investigate the relationships between different type of flexibility and new emergent technologies, and also the relationships between flexibility types and derived reconfiguration cases. The design is conceptually depicted in Figure 30. The model distinguishes three main source factors of flexibility, four type of flexibility that have an impact on the production system, and seven core technologies, which allow reconfiguration and reorganization of the MES level. Through this framework the main purpose of this study is also highlighted.

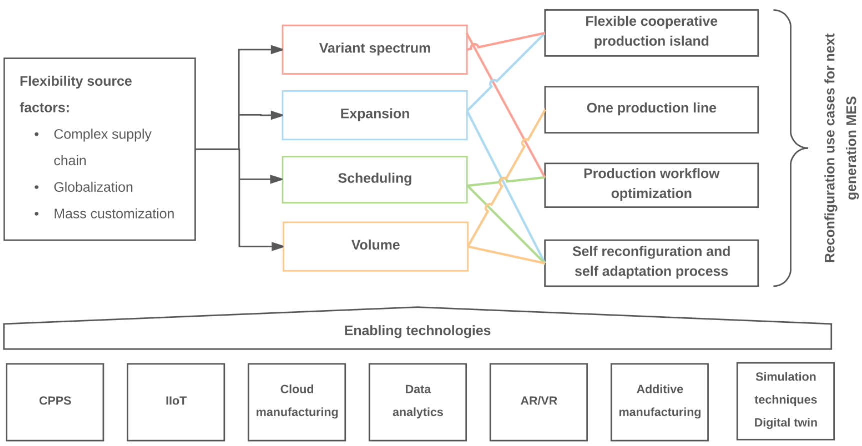

Figure 30 Conceptual model describing the relationships between flexibility source factors, flexibility types and reconfiguration use cases

Authors start by investigating the source factors, which implicate different flexibility types, then identify and analyse the current core technologies, and finally compare the aforementioned technologies with respect to different reconfiguration cases, which represent the requirements for improving MES. According to the hierarchical structure of the conceptual model the identified use cases respond to specific challenges from the manufacturing environment that make necessary a factory to go through new ways of production configuration.

A practical view with respect to the application of the Industry 4.0 enabling technologies is provided in order to understand the actual consistency resulting from the adoption of the proposed model and the related technologies.

As previously mentioned Industry 4.0 embraces various technologies and presents different application fields, many of these will influence planning criteria of next generation production systems. Table 10 shows the mapping between enabling technologies and the related application field. The proposed mapping allows comprehending the relevance of CCPS, IIoT, AR/VR and simulation techniques for the development of next generation of production systems.

In this direction through the machines connection, the product and components traceability, an intelligent network is built with the aim of control autonomously production processes in quantitative and qualitative terms.

One evident objective of industry 4.0 is to translate information not only for humans but also for machine and robots. An additional application is that the product itself is a collector of data and information and it should be able to transfer these data to production processes, controlling and improving them.

The aim is to achieve a new paradigm in which real and digitalized' world can interact. This combination is very complicated, but advantages can be huge because the digitalization of the whole production systems can affect the economic sector.

In the next section a list of reconfiguration cases is provided in order to analyse better the application of such technologies with respect to MES.

Table 10 Mapping between enabling technologies and production application field

Application field	CPPS	IIoT	CM	DA	AR/VR	AM	ST	Level of Interest
Design of industrial systems	x	x	x	x	x		x	High
Design of production processes	x	x	x	x	x		x	High
Logistics		x	x	x	x		x	Medium
Management of production systems	x	x	x	x	x	x	x	High
Maintenance	x	x			x		x	Medium
Safety of production systems	x	x		x	x	x		Medium
Sustainable production systems	x	x	x	x	x	x	x	High

3.2.6.1 Requirements and capabilities for the next generation industrial systems

In this section specific requirements for the next generation of industrial systems are derived. Starting from the flexibility source factors and the flexibility types, requirements are extracted thanks to the performed literature review, which portrayed the state of the art of industrial systems respect to the Industry 4.0 principles and the application of flexible paradigm such as Plug&Produce, decentralized and individualized production. In fact, the reconfiguration use cases are developed with the aim of realizing the decentralized and self-organizing Industry 4.0 principles.

As emerged by the qualitative literature review the main technology, which could drive these challenges, is CPPS. For these reasons the following use case are based on this paradigm and supported by advanced IT services such as data analytics, simulation and the whole cloud computing technologies. The decentralized and self-organized production are based on the integration of different elements which all are intelligent, therefore each production element know its skill, capabilities, position and needs, there is no need of central coordination [82].

Summarizing, the advantages of this production paradigm are: i) reduction of breakdown, therefore installation and maintenance costs; ii) reduction of engineering, reprogramming or rescheduling activities; iii) increase in flexible placement production; iv) continuous production optimization; v) energy efficiency and waste reduction and vi) customer centric approach, which supports the highly individualized and small production.

The benefits of decentralized and self-organized production can be evaluated through the development of flexible and reconfiguration use cases which are: 1) Flexible and decentralized production islands; 2) One production line; 3) Production workflow optimization and 4) Self-reconfiguration and self-adaptive processes.

Flexible and decentralized production islands

The aforementioned shift from mass-production to mass- personalization is one of the key drivers for flexible, sustainable and decentralized production system. The aim is to organize production in cooperative and flexible islands. Each unit in this path is able to cooperate with human or robot, specifically, production islands can interact with one to another and can do specific job within the production processes. This flexible layout allows producing many different product variants, changing in production modules in a short time (Variant spectrum and expansion flexibility) and strongly reducing in waste.

Advantages of using decentralized systems make all elements to be intelligent. In fact, each element is aware of their state, capabilities and needs. There is no need to reprogram, reroute, or reschedule tasks. Another advantage is the reduction of single point of failure. In large complex systems a small failure at a high level can shut down an entire factory. When a production island fails, other production island will take over its task without any notable delay. This significantly reduces the effect of failures of part of the production system [82]. This use case requires several technologies: AM, CM, CPPS, IIoT. Clearly, the CPPS application is essential in order to create a cooperation and interaction between production islands, equipment and components.

Besides, with the aim of knowing state, capabilities and skills on each unit, it is necessary a massive use of CM and IIoT technologies which allow the integration and sharing of information between different factory levels.

Finally, the AM when considering low-volume production, may offer an alternative that could result into shorter lead times and decreased total production costs. In addition, the introduction of AM in a production line can increase flexibility, reduce warehousing costs and assist the company towards the adoption of a mass customisation business strategy.

One production line

Due to the current trends in manufacturing systems, an increasing demand for multiple models and variants of products have been shown. It is necessary the development of one production line for product variants, each variant in the desired volume could be produced on the line matched to customer specifications (variant spectrum, volume flexibility).

Therefore, longer production life cycles with highly flexible and agile manufacturing systems are necessary. It is also important of an early product influence in order to integrate a new product variant on an existing production system. Furthermore an approach of virtual product integration is necessary in order to show the virtual rump commissioning [120]. This use case requires various technologies: AM, CM, CPPS, Digital twin, IIoT and VR/AR. Also in this use case is fundamental the contribution of technologies as AM, CPPS, IIoT and CM which as in the previously case allow cooperation and interaction between not only physical unit but also the information flow.

Moreover, it needs also tools as Digital twin which provide information in order to schedule and control material flow, update changes that have been applied to the plant and simulate the alternatives and visualize the effect of each alternatives. Finally, VR/AR allows reducing costs by virtual tests, which analyse the effective integration between new product variants and the existing production line.

Production workflow optimization

Production processes need to be adapted due to the turbulences caused by customer demand and individualized production. The CPPS application enables the use of well-adopted process modelling and execution workflow in the context of manufacturing companies and tracking of activity flows in the real world [121].

These workflows allow modelling production processes in terms of route, energy efficiency, processing times and transportation time (scheduling flexibility).

Optimizations in the production workflow are then derived from the information collected from CPPS, IIoT, CM and Digital twin. This process of integration and information sharing allows on one hand self-optimization of production workflow and on the other hand a self-learning of production units.

This optimization case needs several technologies: Data analytics, CM, CPPS, Digital twin and IIoT. The CPPS units can execute data analytics functions during production operation, make diagnostics, prognostics decisions and control optimization in real time. The analytics results in large amounts of data, that is stored in the Digital twin, such that additional analytics can be executed at a later point of time.

This integration of technologies allows the optimization of production processes which thanks to the match action of CPPS which send information through the CM and IIoT technologies, and the data analytics produced both real time and offline (Digital twin) production workflow are updated continuously.

Self-reconfiguration and self-adaptation process

The production process could be stopped by several events such as equipment failure and delivery of material. The scope of this specific requirement is to develop self-reconfiguration and self-adaptive production systems, which allow responding to such occurrence (variant spectrum, expansion, scheduling, volume flexibility).

Self-reconfiguration and self-adaptation concepts such as the Plug and produce capabilities and Digital Twins enable faster reconfiguration of production lines and fast replacement of production modules in case of failure, with savings in costs. Self-reconfiguration and self-adaptation of production equipment and production workflows during production can be achieved by the information collected from the CPPS units or by information captured from factory-level systems [122]. Also this use case requires several technologies: CPPS, IIoT, CM, Data analytics and Digital twin. In this use case, CPPS unit is an independent and intelligent production resource that is able to execute a set of production skills autonomously, or in cooperation with other units.

A CPPS offers its production skills as a service to other technologies, all necessary reconfigurations are handled automatically without manual engineering, in fact, CPPS units are able to configure themselves. This is possible through the application of other sharing technologies such as IIoT, CM and Data analytics, which allow the information sharing and this process of self-reconfiguration and self-adaptation. Activities in this context could be considered such as optimize orders' scheduling, control production performance, self- monitoring respect to the necessity of maintenance diagnostics, learning new skills carried out in simulation (Digital twin).

3.3 Model results (RQ3)

3.3.1 Introduction of problems and approaches for industrial sustainability

The case studies have proved the strategic importance of sustainability and flexibility as competitive dimensions, which create and deliver value for companies.

Concerning sustainability, an additional aim is to understand which strategy can create value for companies. Industrial sustainability is composed of various approaches such as: i) eco-design, ii) industrial symbiosis, iii) material and energy efficiency, iv) remanufacturing, reducing, reusing, recycling and v) reverse logistics.

3.3.1.1 Eco- design

Eco-design is a system of strategies developed in order to control product, process or service improving their environmental compatibility. It is an approach in which various concepts of sustainability flow into.

Furthermore, it takes into account issues related to the whole product life cycle, from raw material extraction, processing of raw materials, production, transportation and use, to disposal and recycling [123].

The aim is to minimize the production of wastes and emissions, while at the same time reducing the usage of new raw materials. Typically eco-design involves various challenges such as:

- Light-weighting and de-materialization;
- Increasing purposes;
- Alternative delivery;

- Optimise "equipment leasing" rather than "product ownership".

Product designers should use eco-innovation, life cycle design, management tools and techniques when planning new products and services. The industry needs to utilise sustainable and clean manufacturing technologies and produce eco-products and services that are based on life cycle design and environmental impact principles.

The re-design of product, process or service aims to:

- Minimize toxic substances: this means choosing the best available materials and technologies, which contain low (or zero) percentages of damaging substances;
- Adopt recycled and recyclable materials for products: this results in a re-design of materials, which requires knowledge about their characteristics and their performances.
- Reduce the quantity and types of materials: ideally products should be composed of only one material, which is easily recyclable.
- Materials compatible during recycling: this results in an easier recycling process.

To summarize, the advantages of an eco-design approach allows reducing: i) material intensity, ii) energy consumption, iii) dispersion of toxins and iv) emissions and waste.

While it enhances: i) use of renewable materials, ii) product longevity or durability and iii) reusability and recyclability.

3.3.1.2 Industrial symbiosis

An additional step in the sustainable development is represented by the so-called IS, it concerns the collaboration between two or more industries, which with specific agreements support the exchange of waste and by-products to be used as raw material for production processes without the usage of new raw materials.

Synergies between industries can lead to benefits major than individual ones and these benefits can be adopted by industries, which operate closeness. Physical closeness, multiple resources utilization, input and output flows' modelling with advantage exchanges bring about a more efficient use of resources and a better consideration of environmental effects [124].

IS presumes that industries collaborate intentionally and organize themselves in order to reach not only a better use of materials, but also a partnership that permit to share strategies and objectives.

It is clear that IS leads to an innovative multy-industry perspective as well as costs reduction due to the resources sharing, strategic view development and strengthening of sharing inclination.

To summarize, IS allows adopting a common approach in order to obtain benefits in terms of economic, environmental and social advantages, in general it allows:

- Turning waste streams, emissions, and discarded materials into stocks for other products and processes;
- Converting negative externalities (waste and emissions) into positive environmental externalities:
    - Reduced pollution and waste to land-fill;
    - Reduced need for raw materials;
- Introducing new product lines, new production processes and technologies, and establish new networks of firms to create co-product streams;

- Obtaining mutually beneficial cooperative management of resource flows through a network.

Additionally, there are different types of IS: i) the simple recycling, scrap dealers achieved through waste exchanges; ii) within an organization, or firm or facility park (the best known example is represented by the British Sugar case [125]); iii) among collocated firms in an Eco-Industrial Park (the best known example is the Kalundborg project [126]); iv) among local firms not collocated; v) among firms organized across a broader region (virtually).

At this point, it is important to highlight that IS can be adopted only if the sharing of materials is economically convenient, thus the costs of recycled raw materials should be less than new raw materials. Another relevant aspect to be considered are transportation costs, in this case the value of the recycled raw materials should be greater than the shipment prices.

In spite of the clear advantages of IS some challenges and barriers to its implementation can be observed:

- Complex interaction of technology, economics, society, and government;
- Technical barriers in matching inputs with outputs;
- Need to understand what may be proprietary processes or practices of the potential business partner(s);
- Regulatory barriers may prevent transfer of some waste streams;
- Planning an eco-industrial park is difficult because without firms there can be no transfers, and even when firms come there is no guarantee transfers will take place;
- Motivational barriers, must be willing to commit;
- Costs of reusing waste streams may outweigh the benefits;
- High transaction costs;
- Business risk associated with tying one factory to another firm's waste stream;
- Private benefits need to be maintained for all participants, and sustained private benefits must exceed costs;
- By-product use is not generally a significant economic driver for a firm.

To conclude, IS represents a direct positive effect on the efficiency of the whole system and enables the decoupling between the value created through material processing or products' manufacturing, and the environmental impact associated to natural resource intake and waste/pollutants assimilation [127].

3.3.1.3 Material and energy efficiency

The problems of scarcity of resources, increasing global population and change in habits are making sustainability an imperative issue, which should be re-modelled in order to optimize the dwindling resources available to mankind.

The management of natural resources and the reduction of the environmental impact of materials and technologies is a relevant topic.

In the last few years, environmental problems have increased due to the current way of production, which is unsustainable.

Change in industrial processes, re-design of products and resources are actions essential in order to improve sustainable development. Therefore, resources, materials and energy must be used in an efficient manner and waste and emission must be minimized.

The purpose of using energy and material in an efficient way is not only an environmental issue but also an economic one, as it gives the companies a more competitive edge due to rising energy costs and limited availability of resources. With this in mind, some actions have been taken, and a decline in energy demand can be seen thanks to efficient processes and modified structures.

However, the potential of increasing energy efficiency has not yet been fully exploited in relations to new business models and innovative technologies. In fact, various researchers suggest that the current energy use can be reduced by 50% without any loss of performance.

Regarding material efficiency, it should not be applied just to the most well known resources such as oil and gas, but also to other materials such as metals like copper or zinc. The use of these materials is huge and future access to them will be limited. For these reasons, it is imperative that these issues are now fully recognized as important factors of competition and innovation, and governments and industries should take tangible actions in this direction with the aim of reducing their consumption.

Finally, energy and material efficiency are often managed as separate entities, this is wrong, they are complementary and their integration can give more effective results.

3.3.1.4 Remanufacturing, reducing, reusing and recycling

Remanufacturing, reducing, reusing and recycling are core entities of new business models, as remanufacturing has been well covered in the previous sections (section 3.1.2), here reducing, reusing and recycling are analysed.

Reduce, reuse and recycle are the mantra of the waste hierarchy, which aims at protecting and preserving resources and the environment. There is an urgent need to reduce the intake of virgin materials in the production processes, increase the recycling rate and use waste as resources. This improves efficiency.

The scope is to create useful advantages and value resulting from waste. Positive externalities such as resources saving, energy and material efficiency and waste and emission reduction are trigged in order to improve the sustainable development and create jobs.

Reduce

The primary objective concerning reduction is waste management and particularly to reducing waste at the source.

Generally, waste is generated by i) inefficient use of resources and ii) bad planning.

Reduction activities, mainly involve the curbing of material intensity, making more goods with fewer inputs. Many industries are facing this issue by light weighting their products. At this point it is important to underline that companies must find a balance between material reduction and quality and performance of the products, which should not be compromised.

Reuse

Reuse implies using the same product more than once, be it in its original form or otherwise. Reuse can also imply donating products to charity/community groups or repairing them. With this in mind, a shift from a culture based on consumerism to one based on “make do and mend” is necessary in order to support this concept.

Regarding manufacturing companies, reuse is quite complex. Products to be reused need extensive remanufacturing such as disassembly, cleaning and replacement. It is for these reasons that we speak about “remanufacturing” instead of a simply “reuse”.

Reuse can also present drawbacks. From a broad environmental perspective, in many cases it would be better to recycle a product instead of reuse it. For example, it is better to recycle energy-inefficient cars rather than reuse them.

In this direction, Europe has established policies in order to stimulate consumers to retire their cars with low fuel efficiency and buy new ones thanks to government subsidies.

Recycle

Recycling is the last technique in the waste hierarchy, it permits to manage wastes when they are generated and cannot be reused. This avoids sending wastes to the landfill and obtains a value from them. Efficient recycling needs that different materials must be separated; if a product had been designed with this purpose the recycling activity is simpler than a product that wasn’t thought for this scope and therefore the disassembly could be very complex and expensive. With this in mind, electronic products offer one of the biggest areas of opportunity.

Finally, recycling can involve turning the old material into a new variant of the same product or into a completely new product with new functions. For example, glass bottles can be recycled into new bottles or they can be used as road materials for construction projects.

3.3.1.5 Reverse logistics

In the last few years, manufacturing companies have shown a growing interest in reverse logistics (RL). This has resulted in a more in depth study by researchers, practitioners and academics into competitiveness, economic-environmental sustainability, cost reduction and legislative issues.

With this in mind, there are different factors that support these issues: i) improvement of customer service, ii) reducing production costs, iii) adaptation of standards, iv) environmental protection and v) promoting the corporate image of the company.

However, the barriers to its adoption are: i) implementation costs are high and there is a lack of financial support from governments, this in turn can lead to even more costs for violating pollution laws, ii) there is still no proper development of the technologies in the recycling field, iii) there is a lack of community education, which would improve the understanding and global importance of recycling and iv) forecasting supply and demand for recycled products is difficult.

In this PhD thesis we have decided to focus our studies on IS due to our work with company and manufacturing strategy and value modelling topics, it can be defined with the following statement (Chertow):

“Industrial symbiosis engages traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and/or by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity”

As Chertow (2007) stated, synergies between companies are lead by economic advantages resulting from market opportunities. Companies act with their own interests in mind rather than those of legislation and government regulations [128].

This means that IS is a suitable approach in order to create value and competitive advantages, and thus, it is considered as a form of "new value opportunity" [56].

Industries that want to limit "damage control" need to seek "new value opportunities" with the aim of delivering innovative solutions to social and environmental issues and facing sustainable challenges.

IS, as a new value opportunity, allows the switch to renewable, recyclable and recycled materials, waste reduction, and an improvement in efficiency and productivity. Thus it guides companies towards a closed loop reuse of waste.

Companies have many motivations to shift to an IS approach:

1. Business: this means that shared resources reduce costs and/or increase revenues, and therefore business can be more profitable and competitive;
2. Long-term resource security: this means that companies can preserve critical or scarce resources such as energy, water and specific raw materials;
3. Regulations: this means that regulations or government legislation can push companies to i) increase efficiency of resources, ii) minimize energy consumption and iii) reduce emissions, pollutions and wastes in order to revitalize urban and rural sites, promote job growth, and encourage more sustainable development.

There are many positive factors that affect companies, the IS approach is still underdeveloped in terms of practical applications compared to its theoretical opportunities. Therefore why are there so few cases of it? As we have highlighted in section 3.3.1.2 IS presents many technical, regulatory and motivational barriers. In addition, to the traditional issues of IS there are operational, financial and behavioural challenges arising from its integration across companies.

The scope of the model-based approach is to arrive at a better understand of how IS impacts on companies in terms of value captured, value missed, value destroyed and value opportunities.

3.3.2 Value mapping model for industrial sustainability

Sustainable manufacturing is becoming increasingly important. This requires a sustainable industrial system that differs from today's global industry with different business models, creating different products and services. The evolution towards a 'sustainable' industrial production system requires a holistic approach, with a fundamental reassessment of value creation. In order to achieve this target a system design approach is required. An existing and specific MVMM is used as a value-mapping framework to help firms in creating value propositions better suited for sustainability, considering economic, environmental and social perspectives.

Like any business, addressing important sustainability issues requires specific, hard-wired organizational support, capabilities, and measurement.

As highlighted by Smith et al. [129], achieving sustainability in manufacturing requires a holistic view spanning product design, manufacturing processes, manufacturing systems, and the entire supply chain. Such an approach must be taken to ensure the economic, environmental and societal goals of sustainability are achieved.

Related works in this context are in two domains. On the one hand there is research regarding industrial symbiosis and on the other hand research in the field of value modelling.

The value mapping model now combines the two perspectives by holding on to the hierarchical structure of value proposed by Bocken *et al.* (2014) [56] (Figure 31), as well as respecting internal and external factors. This combination also leads to further review considering evaluation regarding the relationships between these factors.

Thus, the purpose is to present an overview regarding sustainability trends, implications and possibilities that could affect manufacturing companies and supply chains, with the aim of creating a model that allows different dimensions of industrial sustainability (economic, environmental and social) to be mapped.

The hierarchical structure of value proposed by Bocken *et al.*is composed of:

- Value captured: “represents the positive benefits delivered to stakeholders”;
- Value missed: “represents cases where stakeholders fail to capitalize on existing assets, capabilities and resources, are operating below best practices or fail to receive benefits they seek from the network”;
- Value destroyed: “is negative outcomes of the business and concerns the damaging social and environmental impacts of business”;
- Value opportunities: “firms will need to go beyond “damage control” and seek out new value creation opportunities to deliver novel solutions to social and environmental problems that begin to address the wider sustainability challenges directly”.

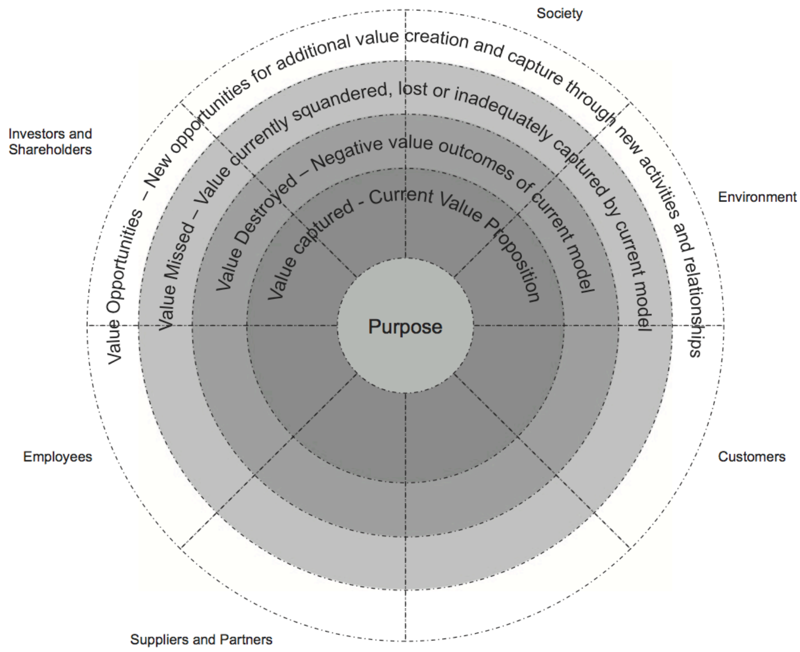

Figure 31 Value mapping tool proposed by Bocken et al. (2014)

Starting from these definitions of value, we have developed a value-mapping model with the aim to provide a guide for manufacturing companies, in order to understand what sustainability trends are fundamental to the manufacturing environment.

The value-mapping model adopts the structure of the MVMM, in order to include internal and external influence factors analysing them with respect to the triple bottom line approach. The value-mapping model starts from the core concept of the MVMM, using the structure of external influence factors (Trends), internal influence factors (Implications) and Possibilities, and also applies the value map by using the aforementioned contents, and the concept of relationships between the value map items.

External factors

The external view represents trends; they are sustainable challenges that have an impact on the manufacturing environment. This section gives a background on the challenges associated with embedding sustainability into corporate performance management. Examples of trends could be for instance “Manage environmental changes” and/or “Reduce energy consumption”. Due to the different markets in which companies operate, the trends might vary from scenario to scenario and related industrial context.

While there might be trends, which are globally valid, there are also trends which are only true for a certain branch of industry. It is important to study the environment of the company and the domain in which it operates in order to identify a valid set of trends. The external view is followed by the analysis of the internal process and strategies.

Internal factors

After the market related view, the MVMM suggests reviewing the implications. The goal thereby is to identify the strategy of the company and how it is achieved. Nevertheless when analysing the company, it is mandatory to understand the business side and production side, since they should fit in the overall strategy of the company. The purpose of this step is to set up a system that identifies critical areas, which have to be addressed.

After identifying the implications, it is important to further specify the context in which the sustainability demand occurs with the analysis of the Possibilities.

Possibilities

The identification of the context consists of selecting the correct functional areas or practices, which need a detailed analysis. Focusing on production, these practices are the functional areas in the MOM domain.

Starting with the analysis of the manufacturing strategy, and then focusing on sustainable industrial practices brings out an alignment of manufacturing strategy with business strategies.

Relationships in the value-mapping model

From a value modelling point-of-view, capturing the environment of the given scenario by identifying the external and internal influence factors and mapping them is necessary to find out which domain specific market trends fit to which domain specific project targets.

Besides the general description of the value-modelling model, it is mandatory to explain the application of the model itself. Since the general approach is derived from the MVMM approach it is also possible to create relationships between the different components.

Generally speaking there is the possibility to create a relationship between external influence factors (Trends) and the business strategy (Internal factor) that is used to tackle them. This means there is a certain set of internal influence factors that fit to a certain set external factors.

Furthermore, after the assessment and the definition of external, internal impact factors and possibilities, it is possible to analyse these contents through a value analysis, which identifies:

- Positive and negative aspects of value in the company or network;
- Possible sources of conflicting value;
- Value opportunities to improve sustainable development.

3.3.3 Hybrid approach

3.3.3.1 Agent based models for sustainability

Agent-based Models (ABM) or multi-agent systems are a class of computational models designed to simulate action and interaction between autonomous agents. They can be either individual or collective entities, such as organizations, and have the aim of studying the effects at aggregate level. ABMs have gained prominence through new insights on the limitations of traditional assumptions and approaches, and improve computational advances have permitted better modelling and analysis of complex systems and particularly in the field of sustainability. ABMs in the industrial sustainability domain are emerging and various authors have identified the potential value and effectiveness, and advocated these approaches for their characteristics [130]. The key advantage is the ability to take into account heterogeneity and behavioural interactions, which can lead to emergent behaviour that would not be obvious or might be very difficult to foresee in an aggregate model as it could occur in the current manufacturing networks [131].

3.3.3.2 System dynamic models for sustainability

System dynamics (SD) is a methodology developed at the end of 1950s at the M.I.T. in Boston. Often human beings operate in systems characterized by high level of dynamic complexity; these systems could be connected to sustainability, physics, ecology, sociology and economy. SD is a representative method for measuring the long-term dynamics of the complex system, which fits for measuring the dynamics of sustainability. It is a simulation method to identify behavioural changes according to the structural characteristics of a system on the basis of the causal relationships among system factors [132]. The inherent flexibility and transparency is particularly helpful for the development of simulation models for complex sustainability systems with subjective variables and parameters. Therefore, this method can consistently be used to understand sustainability discussions [133].

3.3.3.3 Hybrid approach and sustainability

ABM and SD are among the most important simulation methods available; both of these approaches are used to study the leverage points of complex systems. Advantages and limitations of individual methods were the motive for the emergence of integrated simulation approach. Sustainable systems are complex; they exhibit both detail and dynamic complexity, in fact they represent a form of Complex Adaptive Systems (CAS) because they involve multiple sectors and agents displaying non-linear and non-rational interacting behaviours characterized by feedbacks and time lags. Therefore, we claim that a hybrid SD-ABM approach may potentially better address such issues in a more informative and effective way because they exploit the strengths of both models, while minimizing the drawbacks, providing a more realistic view of such complex systems [134]. Lättilä et all., argue that by using both the methods, they will improve the quality of the model and give more in-sights, but at the same time they highlight the need for further researches regarding the actual simulation models [135]. SD and ABM are developed around the real characteristics of the phenomenon they aim at reproducing and simulating, limiting the use of assumptions. In this way, they provide a useful platform to model non-linear phenomena, in particular, they are able to: i) show the impact of indirect effects on the agents and components of the model; ii) shape relations according to their governing feedback loops; iii) internalize an agents' behaviour (ABM) or system relations (SD) linked to externalities of specific actors and situations [130].

In this PhD thesis we decided to use a hybrid approach based on SD-ABM rather than approaches such as: General equilibrium model (GEM), Input/Output analysis or DES because IS represents a form of CAS involving multiple sectors and agents and displaying non-linear and non-rational interacting behaviours characterized by feedbacks and time lags. Therefore, the aforementioned models are not capable of understanding these dynamic behaviours as well as the hybrid approach does.

Thanks to these desirable characteristics, these modelling tools are able to shed greater light on the world we are living in, characterized by time lag between agents' decisions (governments, households, industries) and non-rational actors. Moreover, providing a closer representation of reality, they are also able to show the "unintended effects" of the introduction of new policy measures, such as the rebound effect.

Finally, it is possible to say that SD and ABM complement each other.

The purpose of this research question is to develop a hybrid model for IS and the main objectives are:

- Assess sustainability in the IS network;
- Simulate the IS network in order to better understand and analyse critical problems;
- Analyse how resources' consumption changes with respect to the symbiosis.

3.3.4 Methodological approach

A hybrid system of ABM and SD has been proposed in order to address the unique characteristics of the IS problem such as: (i) nonlinear properties, which would not allow us to use classic econometric models, (ii) positive and negative feedback, which influence its behaviour.

These behaviours can be fully understood in the interactions of the models. In particular, with SD-ABM hybrid approach we can model a component for SD and/or ABM, but it is only run with the most effective one at a given time. The hybrid modelling and simulation approach are suitable to evaluate the system outputs in both macroscopic and microscopic points of view [136].

IS presumes that industries collaborate intentionally and organize themselves in order to reach not only a better use of materials, but also a partnership that permits them to share strategies and objectives.

In this direction, the adoption of the hybrid approach for IS allows examining different strategies, creating a dynamic environment for agents, which can actively behave in the system and interact with each other.

In the work discussed here, system dynamics have been selected for considering flows and feedback dynamics from an aggregated viewpoint. SD reveals the trend and system-level behaviour explicitly and intuitively.

On the other hand ABMs have been selected be- cause they assume no fixed system structure and the overall system behaviour emerges from individual agent rules, thus making it a bottom-up modelling approach. The IS system has been simulated by the Anylogic tool, which provides both the agents and the SD model. The challenge is to determine:

- Which are the individual behavioural aspects that may favour industrial symbiosis?
- What are the overall benefits associated with the entire industrial network?

3.3.5 Case description

IS has been selected as a proof of concept for the proposed hybrid model. The scope of the model is the creation of an eco-industrial development plan by incorporating the basic ideas of industrial symbiosis, industrial ecology and eco- industrial parks.

The model considers an industrial network made up of 4 firms. Each firm produces a single main product sold on the final market. The production process requires a single input, purchased from the external supply market, and generates a single waste product, which is destined for landfill.

Each firm gets revenues from selling its main product, while production costs are in the form of purchasing and waste disposal. We considered 4 industries: a manufacturer of mechanical components (MC), a steel plant (SP), a cement plant (CP) and a paper factory (PF). Table 11 shows Input/output materials for each industry; while Figure 32 depicts the available links between the 4 companies.

We assume that each firm can send and receive waste from any firm. Each firm within the industrial network is modelled as an agent, who decides whether or not to establish a symbiotic relationship with another firm belonging to the other industries.

Table 11 Input/output materials for each industry

Industry	Input	Output	Waste
Mechanical components	Cast iron	Pulley	Cast iron
Steel plant	Carbon/cast iron	Steel	Slag steel
Cement plant	Sand/mixed metal slag	Cement	Waste water
Paper factory	Wood pulp	Paper	Paper mill waste sludge

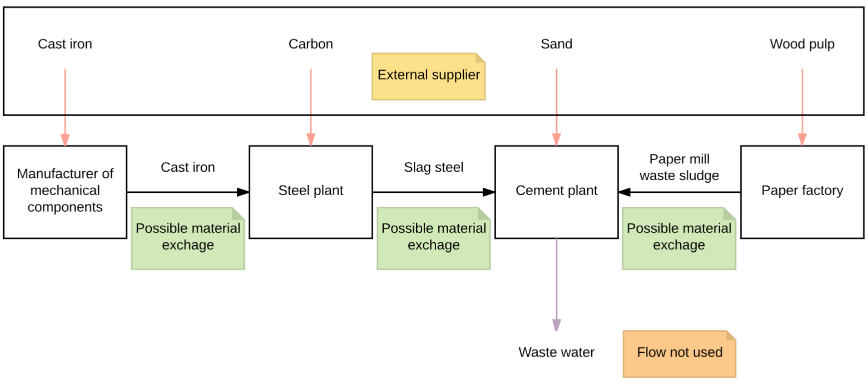

Figure 32 Available links between the four companies

3.3.5.1 Production processes of involved companies

As previously stated, the mechanical components company manufactures cast iron components and sells its wastes to the steel plant.

It has been assumed that the steel plant adopts an Electric Arc Furnace (EAF) technology; this means that the furnace produces high quality steel from cast iron scraps and can reach extremely high (adjustable) temperatures.

Regarding input materials used in EAF, two different process types can be identified:

- Scrap-coal process;
- Cast-iron scrap process.

The difference between the two processes is quite negligible since the amount of cast iron does not exceed the minimum amount necessary to achieve the right carburation. The adoption of one process in respect of the other is mainly related to economic reasons. For our study, we have assumed that the process used by the steel plant is cast-iron scrap casting as the mechanical components company generates cast iron waste.

Cast iron is first tipped into the EAF from an overhead crane. A lid is then swung into position over the furnace. This lid contains electrodes, which are lowered into the furnace. An electric current is passed through the electrodes to form an arc. The heat generated by this arc melts the scrap.

During the melting process, other metals (ferro-alloys) are added to give it the required chemical composition. As with the basic oxygen process, oxygen is blown in to the furnace to purify the steel and lime and fluorspar are added to combine with the impurities and form slag.

After samples have been taken to check the chemical composition of the steel, the furnace is tilted to allow the slag, which is floating on the surface of the molten steel, to be poured off. The furnace is then tilted in the other direction and the molten steel poured (tapped) into a ladle, where it either undergoes secondary steelmaking or is transported to the caster.

Electric steelmaking is ecologically very beneficial since it uses energy effectively to produce valuable material from scrap and hence not only conserving energy but also reduces the waste.

The cement plant uses the wastes from the steel plant. These slags can replace natural aggregates (including materials from rock quarries, alluvial quarries, river basins, excavations, etc.) in the production of cement conglomerates and hence can be used in the field of civil engineering making it also sustainable.

By employing these artificial aggregates, the benefits are remarkable and can be identified in the following points:

- Reduction of new raw materials consumption;
- Creation of sources for supplying raw materials with reduced transport on the road and thus reducing pollution;
- Saving energy and reducing CO2 emissions;
- Equal chemical-physical and mechanical characteristics of steel resulting from the standardized steel production processes.

The cement plant also receives sludge from the paper mill.

This sludge has been analysed in several publications, which demonstrate the possibility of its usage in the cement industry to achieve an "ecoclinker" capable of replacing the classic clinker, as a basic component of cement.

In accordance with these publications, the most common process for producing paper is the Kraft process.

This process uses sodium hydroxide ($NaOH$) and sodium sulphide (Na_2S) for the digestion and separation of cellulose from wood.

It is divided into several phases and sludge and biomass ash are generated as waste thanks to the wastewater treatment. Furthermore, the mud is rich in $CaCO_3$ from the sodification process.

This waste, which has a high degree of alkalinity, is not considered to be hazardous, but if it is disposed of incorrectly it can have a significant environmental impact, damaging water and soil.

In order to avoid its potential adverse environmental impact, this waste must be handled appropriately.

For this reason, its exploitation and utilization in the field of clinker production is desirable as a potential industrial (and non-natural) source of silicon oxide (SiO_2), aluminium oxide (Al_2O_3) and calcium oxide (CaO) and other compounds necessary in clinker formation.

3.3.6 Model development: SD + ABM

In this section the SD and ABM models have been developed and de-scribed. The hybrid model was developed in AnyLogic simulation software. In general, SD modelling uses stocks and flows. Stock is the state of a system and de-scribes its current status. The flow affects the stock and interlinks it within its sys-tem. When the dynamic model is properly developed, the quantitative representation can be simulated.

The dynamic behaviour of the system can be explained by a set of mathematical equations, which are described next. The dynamic behaviours of stock (such as “Raw material inventory”, “Service inventory”, “Final products inventory” and “Waste inventory”) are given by a time integral of the net inflows minus the net outflows. Due to the high number of variables, the specific mathematical formulation and process model description has been illustrated for one of these models, the others have been reported in the Appendix section (Figure 54-56 and the whole model Figure 57).

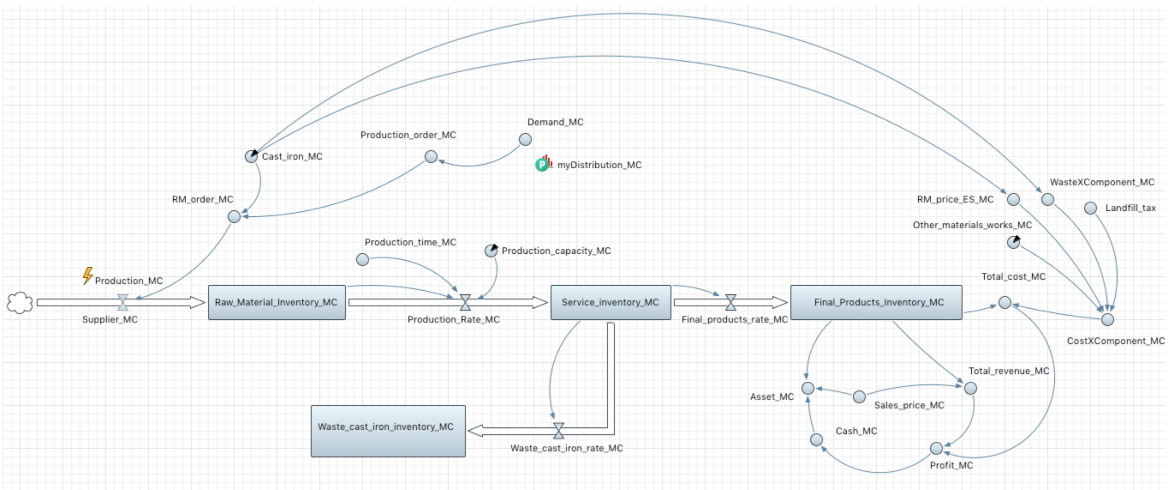

Figure 33 Hybrid model of the Manufacturer of mechanical components

Figure 33 shows the SD-ABM model of the manufacturer of mechanical components, it produces pulleys starting from a customer order. This process has been managed through the variable demand, which is modelled as a random walk. In fact, it consists of a succession of demands, and each demand takes in consideration the previous one. Table 12 shows the demand for each company.

Table 12 Demand of each firms

Week	1	2	3	4	5	6	7	8	9	10
Demand MC [ton]	3500	3310	3233	3180	2914	2806	2883	2915	2920	3012
Demand SP [ton]	28	18	24	16	25	18	26	23	16	26
Demand CP [ton]	10000	9680	9810	9803	9608	9892	10050	9930	9663	10108
Demand PF [ton]	1148	1000	1072	948	800	936	1045	914	778	1078

After an order is received, a production order is generated and at the same time the raw material order is created. The raw material order is linked to the external supplier, which in this specific industry provides cast iron. The raw material flow provided by the external supplier is controlled by an event called “Production MC”. This event allows the material transfer only if the raw material’s level is be-low a specific value. This event stops warehouses filling up in an uncontrolled way.

At the beginning of the simulation, it has been assumed that there are no symbioses between firms, and then only external suppliers provide raw materials. After the procurement phase, raw materials are stored in the raw material inventory in which they wait to be worked. The production phase allows transforming raw materials into final products; this step is done through a constant monitoring of the production capacity, which varies for each factory. Table 13 and 14 show production time and production capacity for each firm.

Table 13 Production time of each firm

	Week
Mechanical components	3
Steel plant	3
Cement plant	1
Paper factory	1

Table 14 Production capacity of each firm

	Ton
Mechanical components	4000
Steel plant	35
Cement plant	10500
Paper factory	1200

During the production process, each firm generates wastes; Table 15 shows the percentage of waste generated by each company.

Table 15 Percentage of waste generated by each firm

	Percentage of waste generated
Mechanical components	5%
Steel plant	9%
Cement plant	5%
Paper factory	8%

Finally, for each firm an economical analysis is provided. In fact, each firm obtains revenues from selling its main product (it has been assumed that all final products are sold), while production costs are in the form of purchasing and waste disposal costs. Figure 34 depicts the detail concerning revenue, cost and profit of each firm of the hybrid model. If there is no link between factories, total costs are the sum of purchasing costs which depends on the raw materials price imposed by the external supplier, waste disposal costs, which depends on the landfill tax imposed by government, and other generic materials and works costs, which take in-to account costs of other raw materials and works with the scope of providing reasonable profit results. These considerations about other generic materials are also made for the material flow in order to respect the mass balance. Revenues are calculated as the product of final goods and the sale price. Finally, there are two last variables, which are Cash and Assets; the first one shows the current level of cash in terms of income and outflow money; while assets analyse the value of the company in terms of profit, cash and value of warehouses.

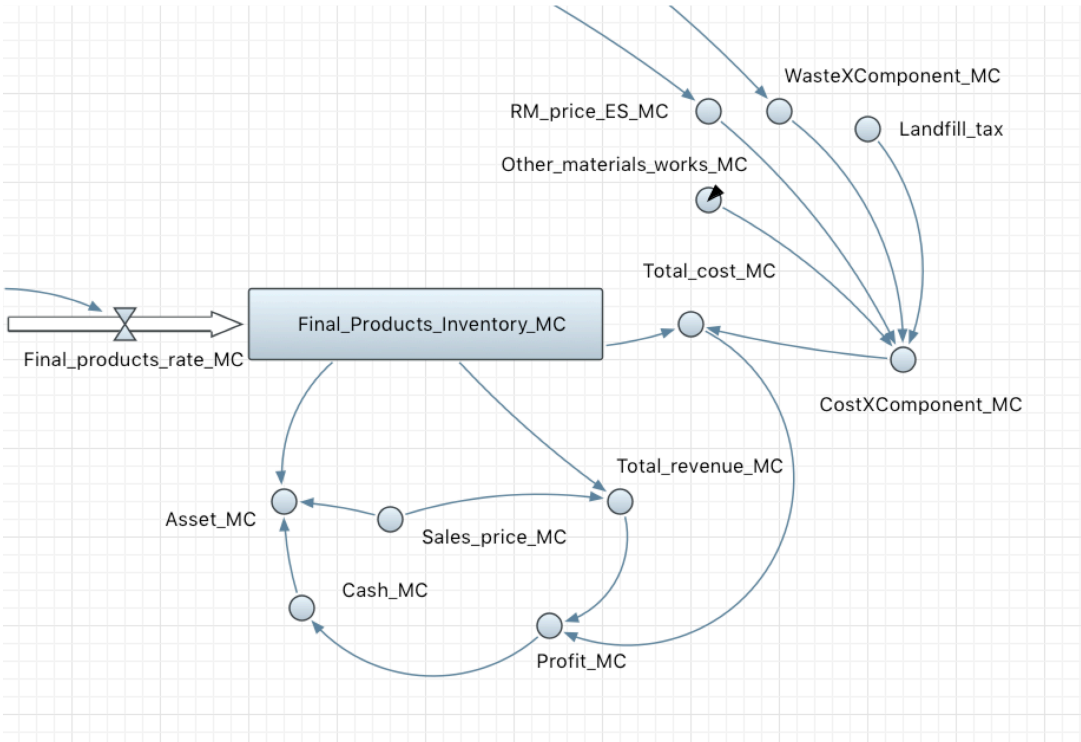

Figure 34 Revenue, cost and profit of the hybrid model

On the contrary, if there are symbiosis linkages between firms, total costs are in the sum of purchasing cost, which now depend on the cost policy adopted by the symbiotic firm, and the other generic material and works. Obviously, waste disposal costs are not mentioned anymore. At this point it is important to underline that in some cases waste effectively becomes “a credit” as iron cast maintains a value, but in other cases waste remains a cost, as the company must pay the other firm for taking its waste away. The firm at the most must pay the landfill tax. In this case revenue is in terms of sold final product and profit derived by the symbiosis.

Finally the whole mathematical formulation is:

$$Production\ rate = min(Production\_capacity\_MC, Raw\_Material\_Inventory\_MC)/Production\_time\_MC \ (1.1)$$

$$Waste\ rate \ = \ 0.05 * Service\_inventory_{MC} \ (1.2)$$

$$Final\ produc\ rate \ = \ 0.95 * Service\_inventory_{MC} \ (1.3)$$

$$CostXComponent_{MC} \ = \ Landfill\_tax * WasteXComponent_{MC} + RM\_price\_ES_{MC} + Other\_materials\_works_{MC} (1.4)$$

$$Total\ cost \ = \ (CostXComponent_{MC} * Final\_Products\_Inventory_{MC}) \ (1.5)$$

$$Total\ revenue \ = \ (Final\_Products\_Inventory_{MC} * Sales\_price_{MC} \ (1.6)$$

$$Profit \ = \ Total\ revenue - Total\ cost \ (1.7)$$

$$Cash \ = \ Initial\ value + Profit \ (1.8)$$

On the other hand the ABM model is described below; the model consists of core entities called agents and links. Figure 35 shows a detail of the ABM-SD approach. In the Appendix section are reported the state charts of each company (Figure 58).

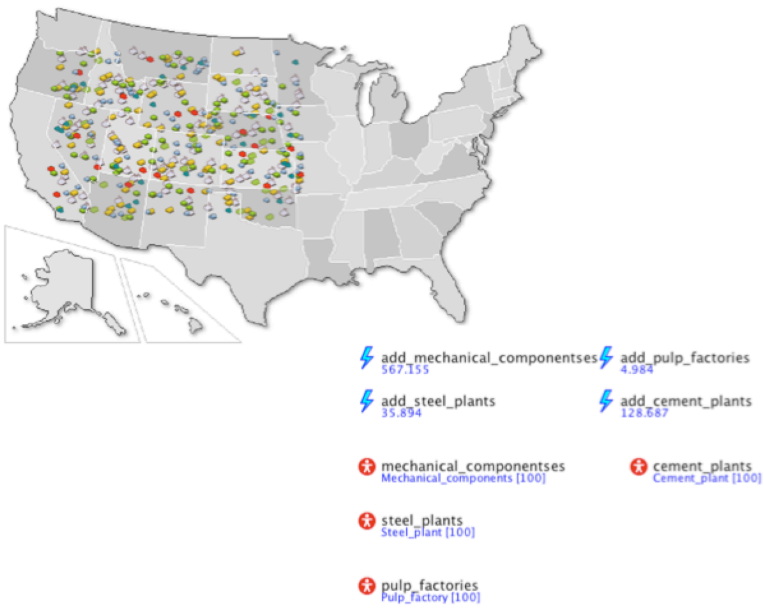

Figure 35 Detail of the ABM-SD approach

Each firm within the industrial network is modelled as an agent, who decides whether or not to establish a symbiotic relationship with another firm belonging to the feasible industry. Therefore, four agents with the same name of the aforementioned firms compose the model, and it has been assumed that each agent has a population of 100 firms. A symbiotic function is defined, which measures the willingness of firm "i" to exchange wastes with firm "j" and vice versa. Shown below is the symbiotic function calculated considering that firm "j" is selling its waste to firm "i". At this point, it is important to underline that, the symbiotic function also takes into account the pre-processing cost, in order to make the external raw material supplier price competitive with the waste price.

$$\textit{Symbiotic function}\ (\mathrm{i} \rightarrow \mathrm{j}) = \textit{Money from}\ (j \rightarrow i) - \textit{Preprocessing cost}(i) > -\textit{External supplier raw material price}\ (1.9)$$

$$\textit{Symbiotic function}\ (\mathrm{j} \rightarrow \mathrm{i}) = \textit{Money from}\ (j \rightarrow i) \leq \textit{Landfill tax}\ (1.10)$$

The abovementioned symbiotic function will be calculated in the state chart of each agent, but the required data is captured from the SD model. The state chart of each agent is composed of two states "No symbiosis" and "Symbiosis". To move from one state to another, it is necessary that the symbiotic condition is verified. Thanks to the agents network, another important variable has been introduced, the Green Image Factor (GIF). In fact, IS has a positive impact on the company image. Therefore interestingly as green product, IS can result in two benefits: i) product price could increase, ii) raise in number of sales. Also in this case, GIF is calculated thanks to the introduction of an event "Calculate GIF", which takes data from the SD model.

Furthermore, the ABM model allows implementing another important aspects of the firms' life cycle: birth and death. In fact, accordingly with the profit generated by firms that is visible in the SD model, new firms/agents are pushed to enter into the market while other ones must leave the market caused by high costs.

To conclude, as previously discussed, the SD model considers flows and feed-back dynamics from an aggregated viewpoint, while the ABM model describes in a clearer manner the behaviour within the company.

3.3.7 Results

In this section the results obtained from the simulation runs are reported and discussed following the two research questions. In the following Table (16), simulation parameters are reported.

Table 16 Simulation's parameters

	Simulation parameters
Model unit time	Week
Landfill tax	18€/ton
Input purchasing cost MC	1800 €/ton
Sales price MC	208 €/Pulley
Input purchasing cost SP	250 €/ton
Sales price SP	1200 €/ton
Input purchasing cost CP	20€/ton
Sales price CP	120 €/ton

Waste cast iron price	140 €/ton
Sales price PF	2000 €/ton
Input purchasing cost PF	85 €/ton

We have evaluated five scenarios:

- The base scenario where companies are not in symbiosis;
- Scenario 1: companies are in symbiosis;
- Scenario 2: price of raw materials analysis;
- Scenario 3: price of pre-processing analysis;
- Scenario 4: geographical distribution of IS network.

The base scenario is used to assess company profits and raw material consumption in the absence of a industrial symbiosis: this comparison with others will actually give the idea of how a symbiosis can affect companies.

Subsequently, Scenario 1 introduces the symbiosis: this begins at the first simulation step and stays stable throughout the duration of the experiment as raw material prices and pre-processing costs are exogenous (independent from system trends).

Scenario 2 and 3 check the impact that a symbiosis may have on raw material prices and pre-processing costs (no longer exogenous and constant): the variation of these endogenous variables may also lead to possible symbiotic interruptions.

Scenario 4 is a 10-year projection to forecast if any long-term durable networks appear that can influence the market and environmental dynamics.

In order to validate the model, the various simulations have been repeated 10 times, varying over time the SEED of the simulator.

3.3.7.1 Base scenario vs Scenario 1-2-3

The following box-plot charts are reported in order to compare base line profits to scenarios 1-2-3 for each company (Figure 36-39).

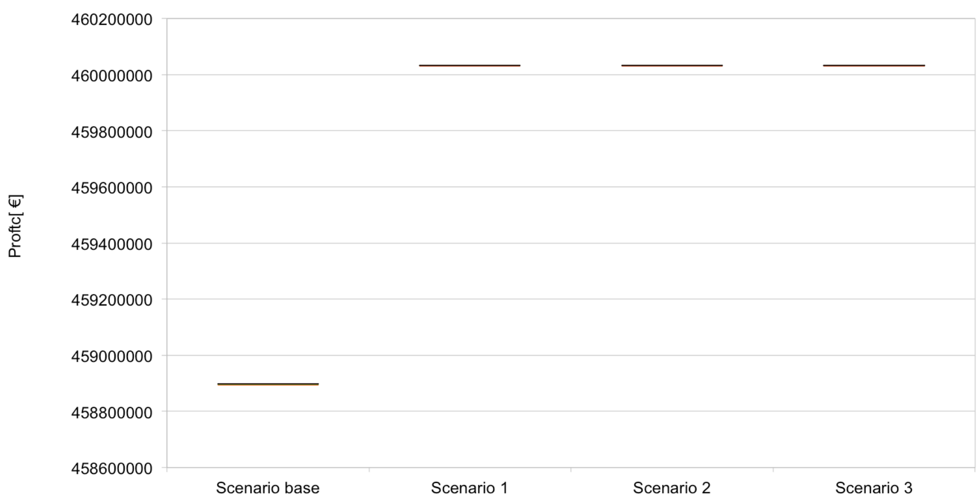

Figure 36 Profit evolution for the mechanical components manufacturer

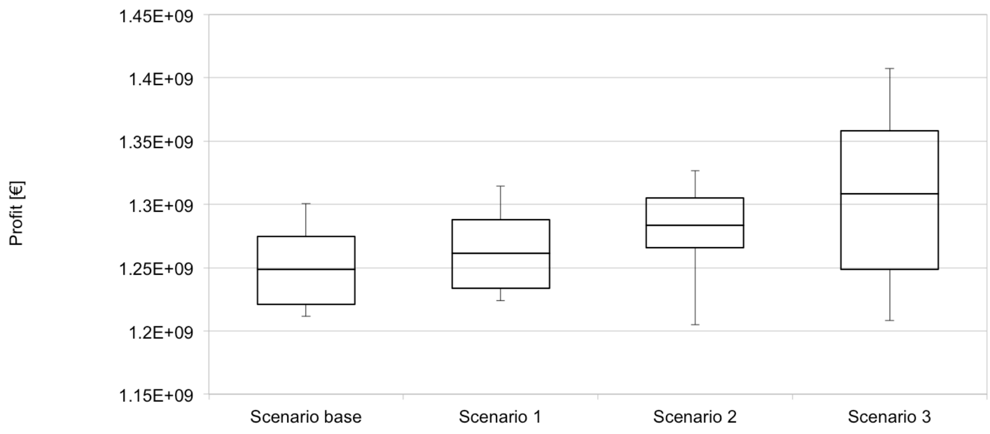

Figure 37 Profit evolution for the steel plant

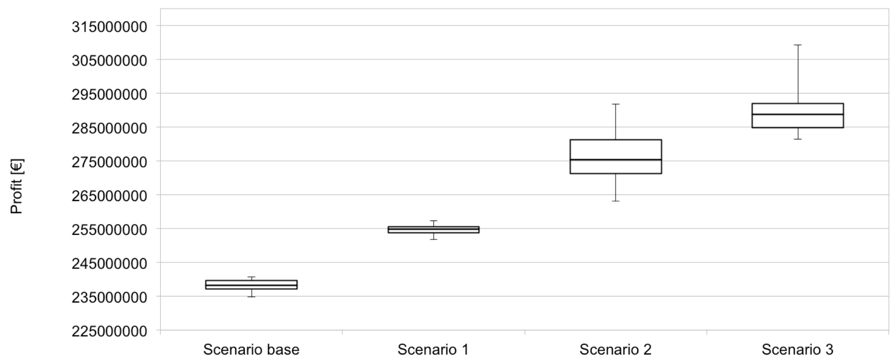

Figure 38 Profit evolution for the cement plant

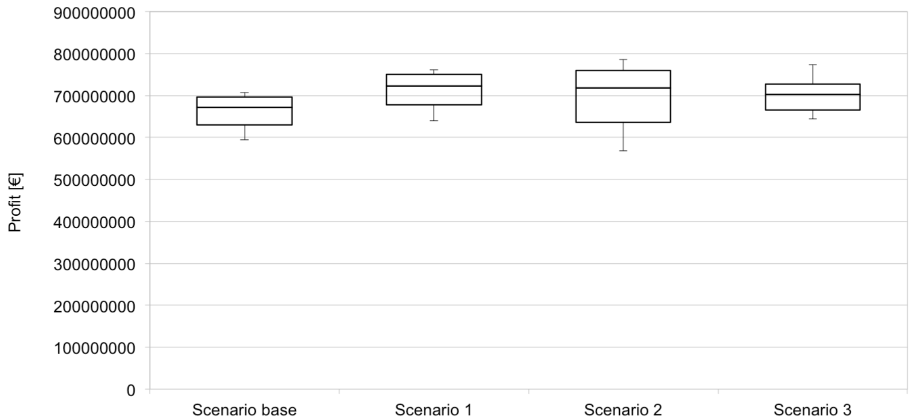

Figure 39 Profit evolution for the paper factory

Analysing and comparing the results, it emerges that benefits can be obtained from a symbiosis in terms of i) environmental impact as it avoids the over use of new raw materials thanks to the waste recycling from the production processes, and ii) economic value, its adoption results in an increase in profits.

We noticed that the difference between profits is small at the beginning of the IS, and then increases over time. This aspect could be caused by i) complex interaction of technologies and process, ii) technical and regulatory barriers.

It is also important to underline that if a company wants to establish a symbiotic relationship with another one, it should take into account several factors.

On the one hand if the symbiotic company buys waste from another company, it could need a re-design of the product. It is essential that the product made with waste must present the same physical-mechanical characteristics and features as the product produced with new raw materials.

The symbiosis between the steel and cement plant in which the steel plant provides inert materials to the cement plant in order to realize the cement mix must follow the aforementioned statement. This means that the cement mix must have at least the same characteristics of cement produced with new raw materials.

With this in mind, the Arvedi Spa Group has developed a sustainable inert material certified for the realization of works in civil engineering. The geophysical characteristics of the material (INERTEX) appear to be better than the characteristics presented by the original product.

On the other hand, the company may need to re-design its processes, as some materials will require different works, space and treatment. This results also in a variation of the industrial plant layout, as it could need i) new machinery and therefore ii) more space.

For example, an additional space for the storage of waste could be necessary.

Instead, if the symbiotic company sells waste, it could be necessary to redesign its processes in order to recover it in a more efficient way. Once the waste has been recovered, it needs to be stored in special warehouses and therefore, this could also results in a re-think of the layout.

The following box-plot charts show raw material consumption for the steel plant company and the cement plant (which are the firms that “buy” waste) and the total raw material consumption compared to the base line (Figure 40-43).

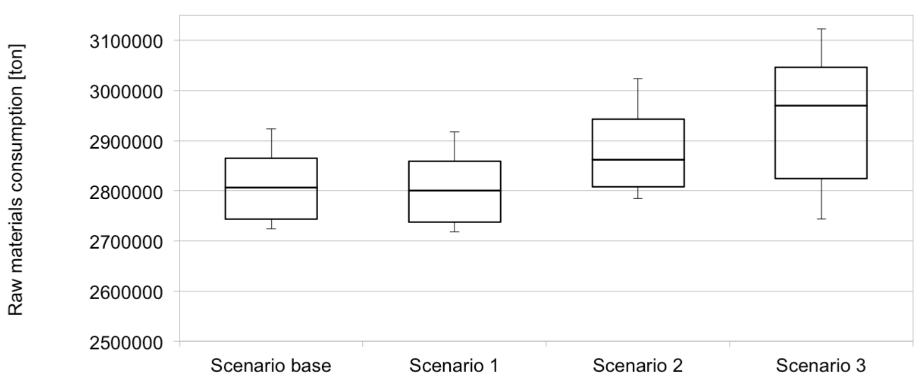

Figure 40 Raw materials consumption for the steel plant

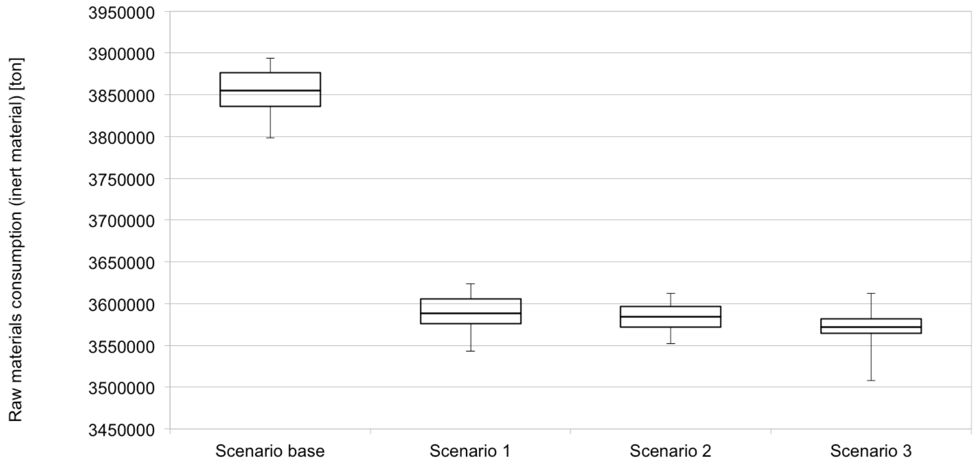

Figure 41 Raw materials consumption (inert material) for the cement plant

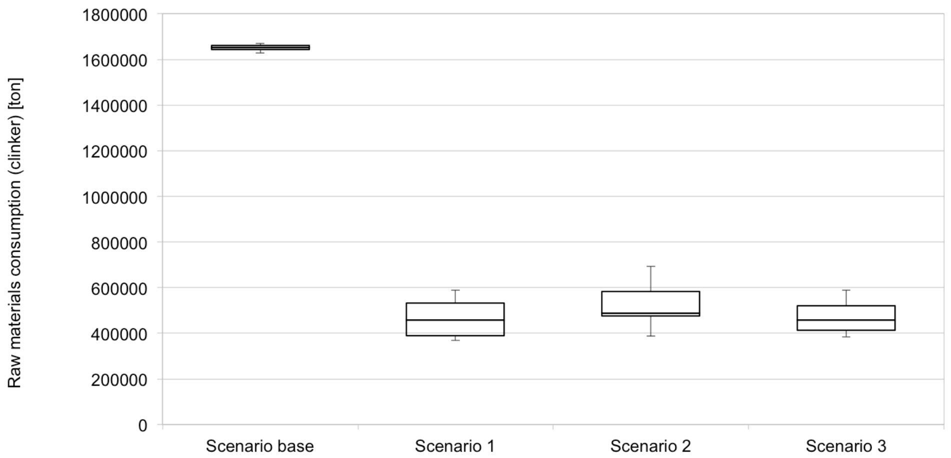

Figure 42 Raw materials consumption (clinker) for the cement plant

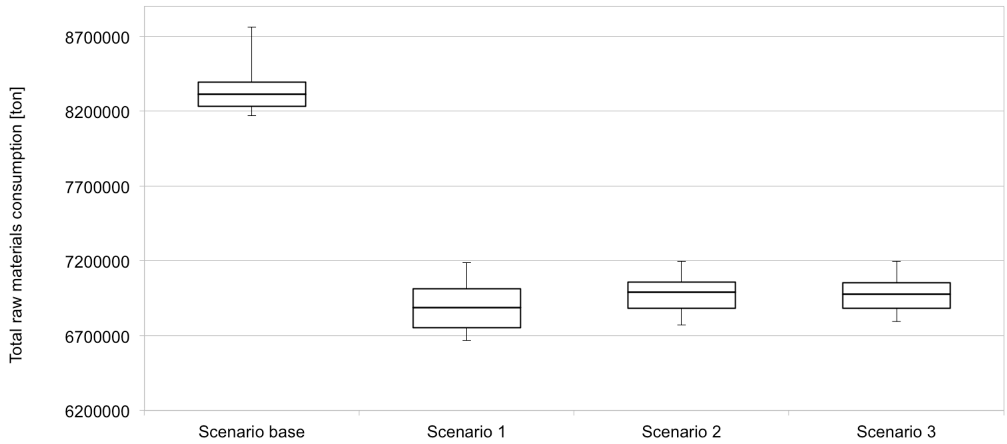

Figure 43 Total raw materials consumption

It is noteworthy that the raw material consumption of the cement plant decreases significantly, while the raw material consumption of the steel plant doesn't follow the same pattern.

This is explained when the company processes are examined. The waste from the paper mill and the steel plant supply the cement plant. These companies work on a continuous process; this means that waste is constantly generated, and therefore the cement plant is able to produce regularly.

The steel plant is furnished by the mechanical components industry, which is based on discrete processes. This generates a waste flow, which is irregular, and therefore the steel plant needs to purchase extra raw materials from an external supplier. In addition, the mechanical components manufacturer is a small enterprise, which isn't able to provide all the raw materials demanded by the steel plant.

This "drawback" is resolved through the ABM model, in which several companies can supply a steel plant.

3.3.7.2 Scenario 2 and Scenario 3

Figure 44 shows simulation results for the raw material scenario (Scenario 2). We find that there is a correspondence between the raw material demand, price and the number of IS. In fact, if external supplier's demand decreases because of the increasing number of IS, there is a resulting decrease in the raw material price. This means that external suppliers in order to be competitive with the waste price need to reduce their price. The behaviour of the market in the long term results in a fluctuations between raw material suppliers' price and waste product price. Therefore, IS will reach a point where it becomes unattractive for companies. There is a delicate balance between the positive effects of GIF and the negative effects due to long term fluctuations in prices, which can bring about system failure.

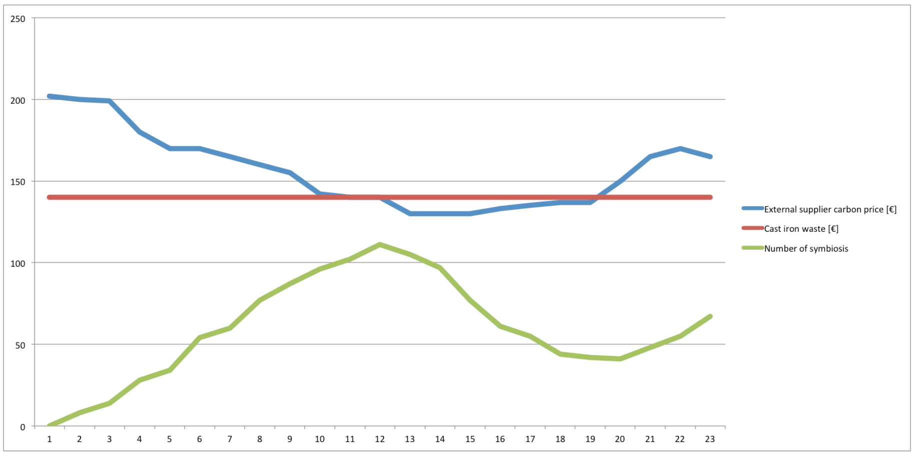

Figure 44 Raw materials' price behaviour with respect to the number of IS

Another interesting behavioural aspect is linked to pre-processing cost (Scenario 3) (Figure 45). When the number of IS is low, pre-processing cost are high; on the contrary, when the number of IS increases, there is a resulting decrease in the pre-processing cost. This behavioural aspect could become clearer considering that at the beginning of the simulation the number of IS is low, so there are few firms that are able to provide pre-processing production, on the contrary when the IS raises, also the pre-processing market becomes more competitive and firms have learned how do it better.

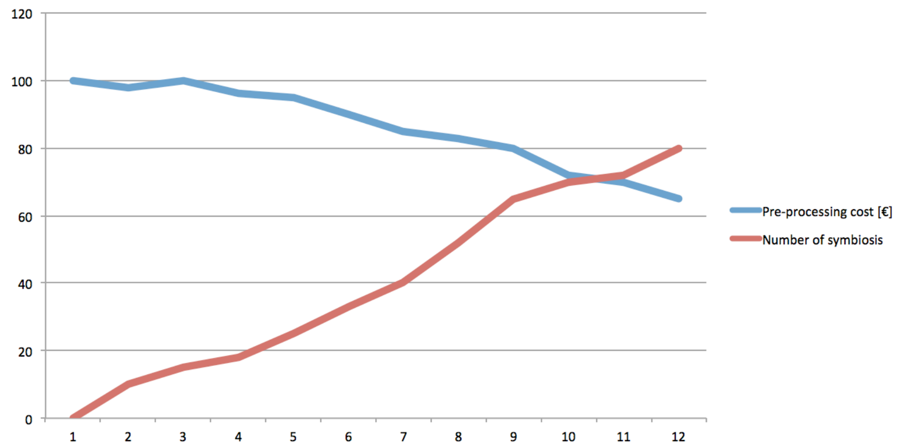

Figure 45 Pre-processing's cost behaviour with respect to the number of IS

3.3.7.3 Scenario 4

The last scenario we want to analyse concerns the evaluation of the geographical distribution of the symbiosis networks, which are represented by the ABM.

The structures of the state charts and the events based on the birth and death of companies show that firms tend to create industrial network.

If certain conditions (Fitness function) are verified, the companies that make up the SD become symbiotic and consequently the industrial sectors of the ABM will enter into symbiosis and establish connections with the nearest agents. The abovementioned symbiotic function will be calculated in the state chart of each agent, but the required data is captured from the SD model.

Obviously, there will be companies that for logistical reasons will not enter into symbiosis and will be penalized by the model, which, with a variable endogenous mortality rate (whose value is proportional to the quality of symbiosis in terms of profits and temporal stability), will be removed from the system.

At the same time new companies flourish within the model in order to establish symbiosis with existing companies with a birth rate directly proportional to the significance of the symbiosis. These series of events determine the creation of macro-networks of industrial symbiosis. The following figures (Figure 46-53) illustrate a ten-year projection of the development of symbiosis networks. This forecast could influence the location of a new plant. If a significant long-term symbiotic network is established, that area could be the best solution for the location of a new plant.

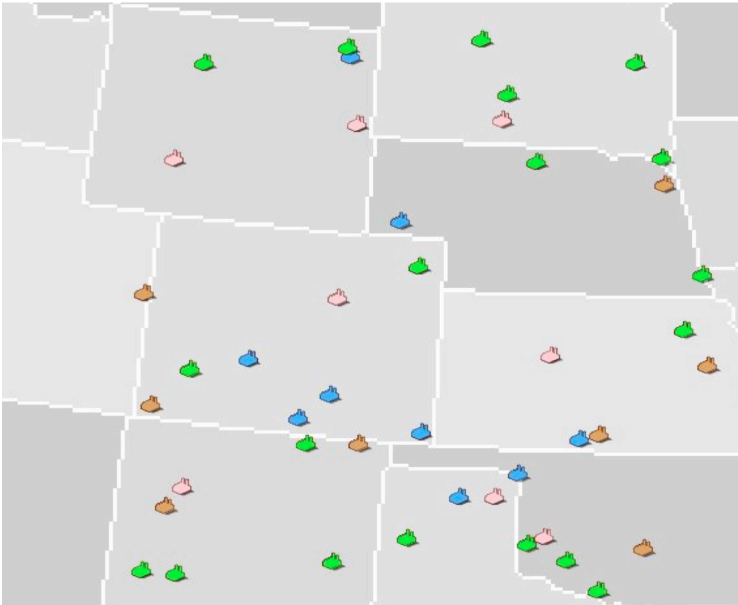

Figure 46 Geographical distribution of companies at the beginning of the simulation

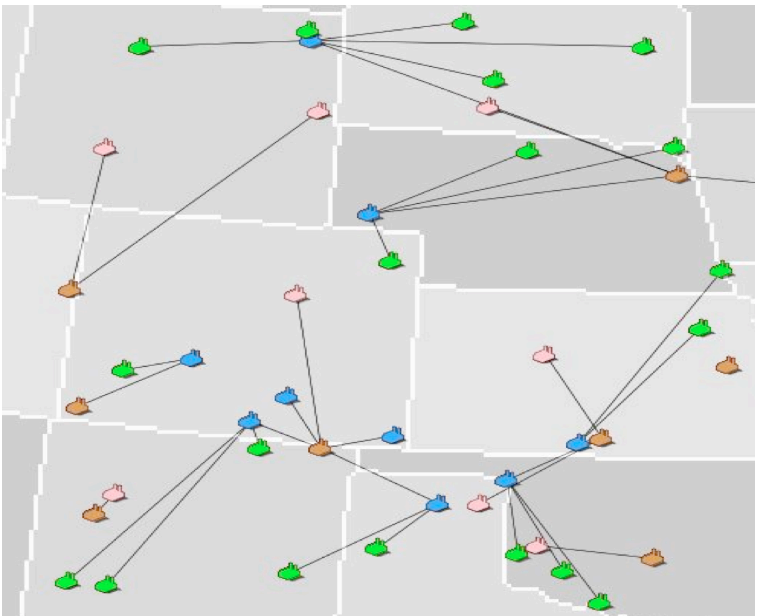

Figure 47 Geographical distribution of companies at the second year

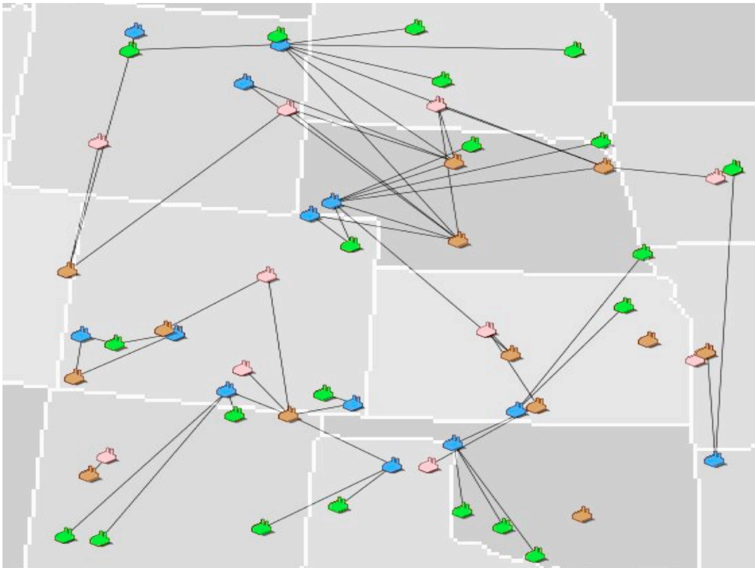
Figure 48 Geographical distribution of companies at the third year

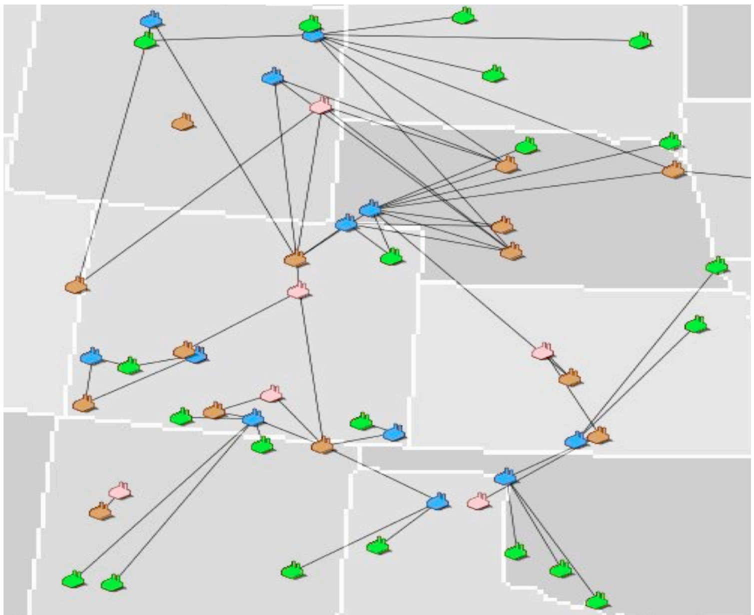
Figure 49 Geographical distribution of companies at the fifth year

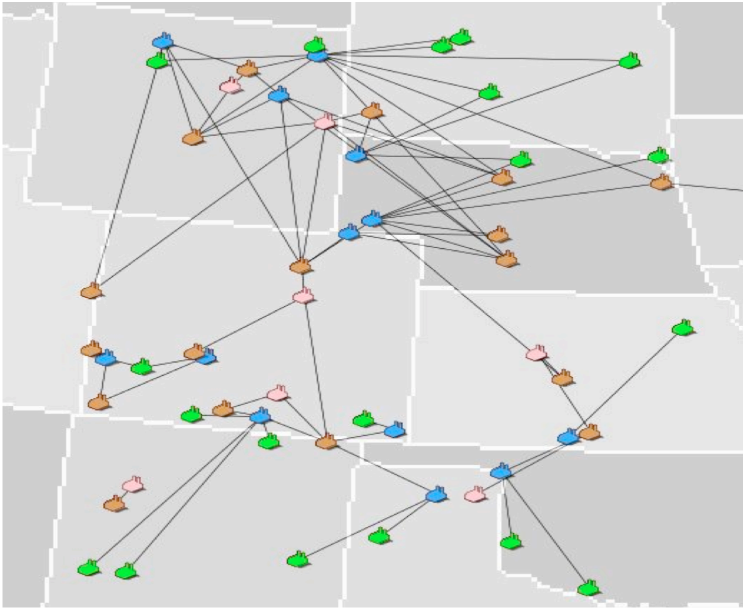

Figure 50 Geographical distribution of companies at the sixth year

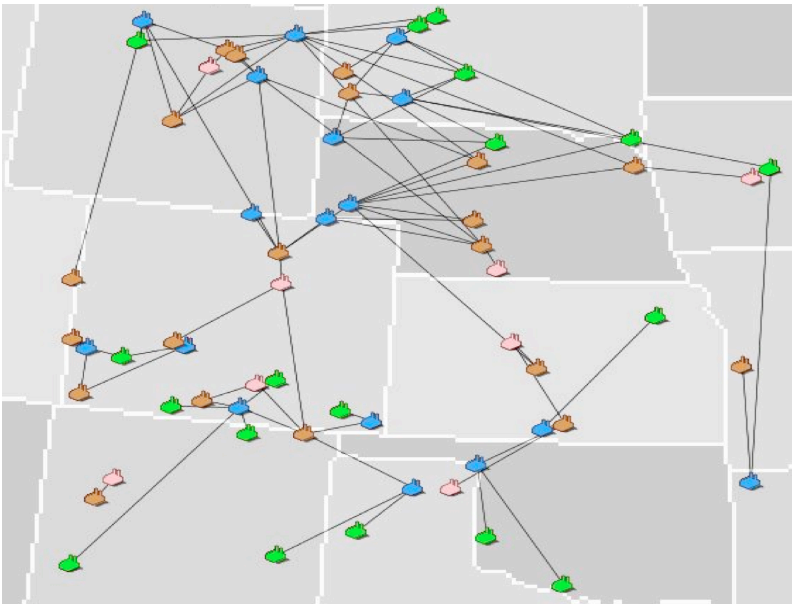

Figure 51 Geographical distribution of companies at the eighth year

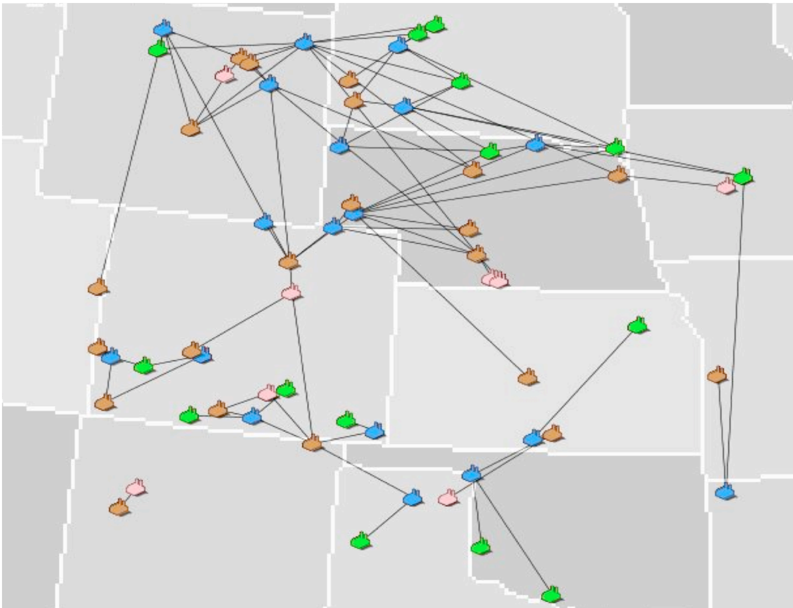

Figure 52 Geographical distribution of companies at the tenth year

Thanks to the results, we can say that:

- *Value captured*: represented by i) profit increases, ii) use of waste as an input, iii) reduction of raw materials and iv) creation of value networks;
- *Value missed*: potential for sharing resources that are not exploited, for example the huge amount of water used by cement and paper production can be redirected, thanks to wastewater management;
- *Value destroyed*: fluctuations in the raw material and waste product prices reach a point where IS becomes unattractive for companies. There is a delicate balance between the positive effects of IS and the negative effects due to long term fluctuations in prices, which can bring about system failure;
- *Value opportunities*: represents the improvement in the symbiosis networks, and increases resource sharing.

4 Discussion

In this section, we discuss the results from the survey-based, the case-based and the model-based approaches.

These results are categorized with respect to the research questions.

4.1 RQ1: What are the emergent manufacturing competitive priorities/dimensions?

The results of the survey and case-based approaches show that the most important competitive priorities are flexibility and sustainability.

We have analysed two previously performed surveys:

1. The industrial point of view “Towards the identification of important strategic priorities of the supply chain network An empirical investigation”, Tsironis and Matthopoulos (2015);
2. The literature point of view “The evolution and future of manufacturing: A review”, Esmaeiliana, Behdadb, Wangc (2016);

The first contribution develops a framework of strategic priorities, which analyses the assessment area that should be improved.

A survey was carried out on 200 companies in order to develop the aforementioned framework and describe the most important strategic priorities for achieving a competitive advantage.

The study examines the strategic priorities, which influence companies’ performance. These competitive priorities are: flexibility, sustainability, efficiency, quality, customer focus, reduction of production costs and waste.

The framework highlights that customer focus, reduction of production costs and sustainability are the critical priorities, which have a direct and positive impact on efficiency. Whereas, flexibility, quality and waste reduction have a direct and positive effect on customer focus, sustainability and reduction of production costs.

The second contribution analyses the evolution of manufacturing companies towards the smart manufacturing environment, which is continuously changing due to the innovative strategies and technologies introduced.

It studies the development of the companies past, present and future advancement.

As new production paradigms are introduced into the market, companies need to investigate these new technologies and capabilities in order to benefit from their impacts.

Therefore, this data confirms the relevance of our topics (flexibility and sustainability).

The result of this study is to define several areas that need to be studied in more detail. We focus on:

- Environmental conscious manufacturing and sustainable manufacturing;
- Planning aspects: Operating rules and process planning;
- New-manufacturing paradigms originated from data analytics.

The survey also establishes that manufacturing companies need to re-think:

- *Business model:* which should focus on advanced manufacturing, replacing the traditional business model. They will offer a new product experience instead of a traditional tangible product, which realise on flexibility, sustainability and efficiency.

- *Emerging technologies*: these will empower new business models, and improve flexibility, sustainability, agility and re-configurability.
- *Advanced planning and scheduling:* the smart manufacturing environment optimizes processes and introduces new management methods, both should be equally considered.
- *Enabling factors:* they are ICT, innovative technologies, new insights, production paradigms and new capabilities including smart buildings and infrastructures.

From the case-based point of view, we have analysed four companies: i) an automotive components company; ii) a white goods company; iii) a food company; and iv) a soft drink company. The four case studies have been chosen for these macro-characteristics:

- Show strong orientation towards sustainable issues;
- Focus on relevant flexible and re-configurable issues;
- Represent a miscellaneous sample, showing both discrete and continuous processes.

The results of the case studies confirm that flexibility and sustainability are relevant competitive priorities.

This similarity might be due to the fact that the companies are Italian nationals who tend to follow the same competitive priorities practiced in their country.

Regarding flexibility, companies evaluate its relevance as high, and their statements are summarized in Table 17:

Table 17 Companies' statements with respect to flexibility

Company	Statement
Automotive component company	It would like to improve sequence optimization and scheduling management, which will help the company to increase its flexibility towards suppliers and customers. Main benefits could be obtained in the foundry.
White goods company	It shows a great interest in flexible and reconfigurable production systems related to the issue of production configurations and varying volume, particularly it focuses on capabilities that enables the system to easily exchange manufacturing technologies when singular events, such as delayed delivery of supplied parts, or the failure of production equipment could quickly disrupt the production of an entire day. Significant savings potential can be achieved by self-reconfiguration and self-adaptation of production equipment and production workflows during production either based on the CPPS's and work pieces' own state or triggered by information from factory-level systems and external systems.
Food company	It faces fluctuations in demand as it feels the need to keep a safety stock to maintain a high level of service and satisfy customer needs. Both have a negative impact on food waste. Reducing this uncertainty and improving flexibility can create benefits for the company. It means lower inventory costs and an ability to plan production better, fresher products, less waste, and better in-stock position, resulting in higher margins and more sales, and for the consumer, the product is fresher and keeps longer.
Soft drinks	Set-up times, cleaning times and routing flexibility emerged as critical

company	factors. Concerning the primary phase, managers highlight that there is the possibility to produce different recipe in different time with the same line (mixer), or produce different recipe based on the same ingredients in sequence, but it is necessary to consider that after a production cycle, the line needs to be cleaned and re-organized. While the secondary phase mainly addresses the issue of routing flexibility. Managers explained that an increased on routing flexibility is needed in order to interchange the order in which the required manufacturing operations are performed due to congestion, breakdowns and blocking.

Regarding sustainability, companies also evaluate its relevance as high, and their statements are summarized in Table 18:

Table 18 Companies' statements with respect to sustainability

Company	Statement
Automotive component company	It is very involved in the use of sustainability in its processes. Its goal is to continuously improve its performance in terms of health and safety in the workplace and environment. This is a primary goal for the company and it is committed to taking every measurement possible to ensure that it is achieved.
White goods company	The company would be able to analyse each element of its strategy and business model in order to understand what factors influence sustainability. Reverse logistics is another relevant topic for the company. It is that branch of logistics that allows going back to the production chain of a product or system in order to "recover value." The company would be able to recover its products in order to return value derived from its obsolete products.
Food company	Data analytics can help the company use resources in a more environmentally responsible manner, improve their sourcing decisions, and implement circular-economy solutions in the food chain. These technologies would allow the monitoring of quality, efficiency and traceability. From the company's point of view, competitiveness depends mostly on the sustainable factor both from the planet footprint and the waste reduction, keeping in mind the lean thinking principles.
Soft drinks company	It is possible to detect its particular focus and interest on sustainable topics such as packaging and water consumption. Concerning packaging, the design of it aims at reducing, recycling and reusing materials for the safety of natural resources. The company considers packaging as one of the main objective of its environmental management; in fact it pays close attention both to the design of the packages, and their recovery. A system of capturing and storing rainwater has been developed, it allows to re-use water for auxiliary services such as fire protection and sanitary services of the plants. The company also implements a system of cleaning with the aim of reducing energy and water consumption. The huge water consumption both for the production and the cleaning processes needs an accurate management both for economic and environmental purposes.

Thus, we can confirm that flexibility and sustainability are important priorities for companies, and are managed in order to achieve a competitive advantage and therefore create value.

4.2 RQ2: How does flexibility impact on manufacturing companies?

The case studies have proved the strategic importance of sustainability and flexibility as competitive dimensions, which create and deliver value for companies.

Concerning flexibility, thanks to the strategic vision and operational support of Siemens MES, we have decided to investigate this issue more thoroughly.
The scope was to create a model that provides a structural definition of existing flexibility types in line with the heterogeneity of the topic and their composition, as well as providing decision support regarding the identification of the correct flexibility demand of any given manufacturing scenario.

This was a joint venture with the University of Nuremberg due to its inclination to i) automation technology and ii) digital transformation.

All works related to this context are in two domains: i) flexibility and ii) value modelling in manufacturing systems. Both domains are crucial, the research in flexibility is important for the creation of the underlying flexibility model, while the research in manufacturing value modelling is seen as key in constructing the framework for identifying the correct flexibility demand for any scenario.

Figure 53 shows the developed flexibility model.

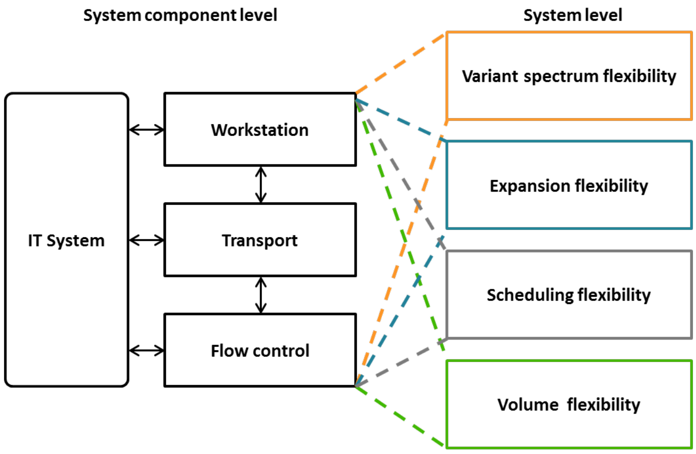

Figure 53: Flexibility model

The purpose of the research question was to investigate the topic of manufacturing flexibility and to develop a framework, which allows companies to identify the impact of flexibility on their environment and processes.

The literature has shown that the topic is extensively covered but there is a lack in identifying the factors, which could cause a flexibility demand. In this research question the MVMM is used to close this gap. The MVMM structure allows identifying the external impact factors and internal strategy that drive the flexibility demand. By adopting the aforementioned structure a flexibility model is developed, showing a possible identification of the four main flexibility types for manufacturing systems, which can be clearly defined and delimited from each other (variant spectrum, expansion, scheduling and volume).

It also shows that a general framework could be used to highlight the relationships between flexibility demand and flexibility type.

The flexibility demand can be derived through the MVMM and the consideration of internal and external factors, leading to a better understanding of the concrete type of flexibility that is needed for the given scenario.

Therefore, the hierarchical structure of the MVMM allows identifying pressure and challenges, in terms of flexibility demand that has an impact on the company environment. And starting from these trends, define specific flexibility types and capabilities that are essential for driving companies to reconfigure their processes.

Especially at this point it necessary to highlight again that these objectives highly depend on the specific scenario under study, however a set of general objectives for industry are provided as a starting point for the assessment with a company.

The goal is to offer a first set of objectives that can be discussed with a company and to sharpen the understanding in order to add more scenario specific objectives that follow the same structure and definition.

There are some limitations to the flexibility model. It is mainly qualitative and does not allow a detailed quantitative analysis. To overcome this limitation further research could build on different approaches towards measuring flexibility in manufacturing systems.

4.2.1 RQ2.1: Which are the main technologies, requirements and capabilities for the next generation of industrial systems to be more flexible and sustainable?

As mentioned, manufacturing companies are facing a continuously increasing demand for flexible production in terms of variety and options due to the possibility that customers have to configure their products.

Starting from the defined flexibility types the scope of this research question is to understand what enabling technologies could support industrial systems to be more sustainable and flexible.

It is necessary to optimise the trade-off between sustainability, flexibility, management of the warehouses, stock and transport for the products personalisation.

To support this, new tools and technologies are required for the configuration of corporate networks to favour and promote the composition of adaptive and interoperable enterprise networks that enable cooperation and communication between the various players in the value chain.

The purpose of this research question is on the one hand identify and define reconfiguration use cases, which supported by digitalized opportunities allow achieving specific type of flexibility (variant spectrum, expansion, scheduling and volume) that has an impact on the manufacturing system and therefore propose an analysis of potential improvements of current MES/MOM. On the other hand use them in order to manage economic and environmental sustainability of the production processes in the ability to gather data relating to the product during production and use, in order to compare it with that envisaged during the design phase. They must be able to supply sustainability metrics to support the decisions on various decisional levels for the various phases of the product’s life and may be used at corporate level or at public decisional level for the localisation of advanced environmental impact management services.

This has been resulted in the development of four use cases, which are designed starting from the aforementioned state of the art provided in response of four type of flexibility identified in the previous research question and the sustainability demand.

The scope in the development of future core requirements for MES is to achieve the capabilities own of decentralized and self-organized production.

The decentralized and self-organizing production aims at achieving rapid reconfiguration and individualized production by design the manufacturing system and its machine and resources through the implementation of specific emergent technologies, which are more efficiency and energy savings.

Therefore, the requirements identified bring to a high level of integration between machines, humans and processes, which reflect to a high level of complexities justified by huge advantages in terms of flexibility and sustainability.

4.3 RQ3: How does sustainability impact on manufacturing companies with regard to industrial symbiosis implementation?

The case studies have proved the strategic importance of sustainability as a competitive dimension, which creates and delivers value for companies.

The scope of the model-based approach is to arrive at a better understanding of how IS impacts on companies in terms of:

- *Value captured*: represented by i) profit increases, ii) use of waste as an input, iii) reduction of raw materials and iv) creation of value networks;
- *Value missed*: potential for sharing resources that are not exploited, for example the huge amount of water used by cement and paper production can be redirected, thanks to wastewater management;
- *Value destroyed*: fluctuations in the raw material and waste product prices reach a point where IS becomes unattractive for companies. There is a delicate balance between the positive effects of IS and the negative effects due to long term fluctuations in prices, which can bring about system failure;
- *Value opportunities*: represents the improvement in the symbiosis networks, and increases resource sharing.

To summarize, the impacts on manufacturing companies with regard to IS can be positive and negative:

- Positive:
    - Improvement in environmental impact as it avoids the over use of new raw materials thanks to the waste recycling from the production processes;
    - Increase in the economic value, its adoption results in a rise in profits.
- Negative:
    - Complex interaction of technologies and process;
    - Technical and regulatory barriers;
    - Costs due to re-design of product, process and plant layout.

5 Conclusions and further developments

The literature on operations management is constantly evolving from the concept development to methods and tools. We can also observe a relevant shift to innovative technologies and production processes, which increase the level of complexity.

In addition, globalization and the very demanding customer have intensified the competition between manufacturing companies not only in the domestic market but also in the whole world.

Due to the actual manufacturing environment of customized products, shorter lifecycles and scarcity of resources, companies are working towards:

- Sustainable production systems;
- Flexible and reconfigurable manufacturing systems;
- Digital transformation.

From the analysis of the current context and the performed literature reviews we can see that flexibility and sustainability have reached the same importance if not greater than traditional competitive dimensions (cost, quality, time and reliability).

Reviewing papers it becomes clear that in the past have rarely attempted to study “flexibility + sustainability” in combination. To address uncertainties resulting from globalization and rapid climate change, organizations in the present era need to embrace sustainability and flexibility.

Furthermore while traditional dimensions have been well established; flexibility and sustainability require more development.

Starting from previously established surveys, we want to investigate if strategy and competitiveness are associated with specific strategic priorities. These dimensions include concepts such as sustainability, flexibility, cost, quality, time and reliability.

Manufacturing supply and value chains require different assessment and evaluation of these strategic dimensions.

The aim of this PhD thesis was to investigate the relevance of flexibility and sustainability within the smart manufacturing environment and understand if they could be adopted as emerging competitive dimensions and help firms to take decisions and delivering value.

In order to prove the relevance and the evolving role of flexibility and sustainability in the current digital manufacturing environment, literature suggested the application of research tools such as survey based approaches, which allow gathering data with the aim of verify the adequacy of contents. Because of the novelty of the digitalization concept within manufacturing companies, we decided to draw our research from previously established survey results.

Company strategies and competitive dimensions can critically change from one industry to another; for this reason and in order to enhance our research, we decided to use the survey results with the aim at studying specific cases belonging to various industrial sectors. We selected an automotive components company, a white goods company, a food company and a soft drink company due to their characteristics and we have validated our results from these various industries towards adopting a CBR.

Finally, we adopted a model-based research to conceptualise specific behaviours. We have assumed the use of model base research in order to analyse the evolution of strategies, due to the adoption of case studies, which are not longitudinal.

Therefore, we have used a mixed research methodology based on survey, case study and model. This mixed methodology has been adopted with the scope of overcoming limitations of individual methods.

The survey and case based approach have proved the strategic importance of flexibility and sustainability as competitive dimension, which creates and delivers value for companies. While the model-based approach allows understanding of how IS impacts on companies in terms of value captured, value missed, value destroyed and value opportunities.

We can therefore conclude that flexibility and sustainability are major factors to be considered when modelling value and evaluating investments in manufacturing companies.

This is in line with some previous contributions, but provides a relevant extension. Indeed, previous results focused only on one competitive dimension and practical validation of those studies were not provided, while in this research we have considered the two dimensions together, and we have validated our results through empirical cases.

Concerning flexibility, we have created a model that provides a structural definition of existing flexibility types in line with the heterogeneity of the topic and their composition, as well as providing decision support regarding the identification of the correct flexibility demand of any given manufacturing scenario. The model can be used to highlight the relationships between flexibility demand and flexibility type. Flexibility demand can be derived through the MVMM and the consideration of internal and external factors, leading to a better understanding of the concrete type of flexibility that is needed for the given scenario.

The proposed framework helps companies in choosing an appropriate type of flexibility and assists them in identifying possible areas of improvement in enablers of manufacturing flexibility.

Concerning sustainability, previous contributions on its modelling considered only traditional simulation techniques; while in this research we have considered an innovative hybrid approach (ABM+SD) rather than approaches such as: GEM, Input/Output analysis or DES because IS represents a form of CAS involving multiple sectors and agents and displaying non-linear and non-rational interacting behaviours characterized by feedbacks and time lags. Therefore, the aforementioned models are not capable of understanding these dynamic behaviours as well as the hybrid approach does.

The hybrid system (ABM+SD) has been proposed in order to address the unique characteristics of the IS problem such as: (i) nonlinear properties, which would not allow us to use classic econometric models, (ii) positive and negative feedback, which influence its behaviour.

About the limitations of this work, this study as most works on competitive priorities, assess responses from managers within each site. While some researchers have criticized this approach (Swink and Way, 1995; Boyer and Verma, 2000), it could be useful in medium companies. Under this environment, it is possible to presume that the SC and R&D managers have a clear vision with respect to the competitive dimensions of their companies. The alignment of competitive priorities represents a needed and relevant aspect of companies.

Other limitations of this work are related to the dataset that includes companies only from the Italian manufacturing industry. Different outcomes could be found in other types of industries. It could be interesting to include companies from the service industry in future studies to see if those industries play a role in the implementation of operations strategy and the realization of subsequent benefits.

As stated, the case studies include only companies from Italy; it is beneficial that future works include companies from other countries.

Even within manufacturing, the limited number of company in each sector (1) does not permit us to highlight differences between the different industry sectors.

These factors can be relevant in order to replicate manufacturing strategies in different environments.

Furthermore, we studied only two competitive dimensions, flexibility and sustainability. Although there could be expected correlations between our competitive dimensions and others, including their specific assessment in future studies will be useful.

Regarding the flexibility model, it is mainly qualitative and does not allow a detailed quantitative analysis. Additionally, a validation with real use cases is needed to verify and improve the model. It is evident that this area still requires significant investigation at the operational and strategic levels.

Finally, at the current state of the SD-ABM model's development, the results are promising, but they still need revision. The model still needs some improvements as well as an enhanced validation in order to deliver more realistic results. However, its design is seen as an approach to modelling multi-agent network systems that may serve as the basis for the development and sustainability of industrial symbiosis. One of the limitations of the model is that transportation costs are not addressed. Even though, the current model is a good foundation for further iterations, and it could be a good starting point in order to better investigate the hybrid simulation field.

Further developments of this work are connected to its actual limitations:

- Increase the heterogeneity of the sample in order to replaced the results to other sectors;
- The flexibility model is mainly qualitative and does not allow a detailed quantitative analysis. To overcome this limitation further research could build on different approaches towards measuring flexibility in manufacturing systems;
- Quantify and transform the proposed MES requirements into target sustainability key figures for the reconfigurable manufacturing system and to detail effective methods for planning future changes;
- Expanding the ABM model, which requires further deeper understanding and abstracting concepts and theories. To enhance the way how we describe companies, more types of them may be introduced as small, medium and large companies. More intelligent agents behaviours should be introduced in order to improve calculation and feedback analysis.
- Additional factors may be incorporated into the model such as transportation costs, energy and water requirements, emission and pollution.
- Improvements in the design of experiment can be conducted when more detailed data can be collected from other projects. While a preliminary robust test was done, such a sensitivity analysis can be expanded to identify all important factors and parameters.

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Nomenclature

ABM	Agent Based Models
AM	Additive Manufacturing
AR/VR	Augmented Reality and Virtual Reality
BOM	Bill of Material
BOP	Bill of Process
CAS	Complex Adaptive Systems
CBR	Case Based Research
CM	Cloud Manufacturing
CP	Cement Plant
CPG	Consumer Packaged Goods Market
CPPS	Cyber Physical production System
DA	Data Analytics
DES	Discrete Event Simulation
DM	Digital Manufacturing
DML	Dedicated Manufacturing Lines
EAF	Electric Arc Furnace
ERP	Enterprise Resource Planning
F&B	Food and Beverage
FI	Fabbrica Intelligente
FMS	Flexible Manufacturing Systems
GDP	Gross Domestic Product
GEM	General equilibrium model
GIF	Green Image Factor
ICT	Information and Communication Technology
IIoT	Industrial Internet of Things
IoT	Internet of Things
IS	Industrial Symbiosis
IT	Information Technologies
JIT	Just in Time
KPI	Key Performance Indicators
LCA	Life-Cycle Analysis
MBR	Model Based Research
MC	Mechanical Components
MES	Manufacturing Execution System
MOM	Manufacturing Operations Management
MRP	Manufacturing Resource Planning
MVMM	Manufacturing Value Modelling Methodology
OEM	Original Equipment Manufacturers
PF	Paper Factory
R&D	Research & Development
RL	Reverse Logistics
RMS	Reconfigurable Manufacturing Systems
RQ	Research question
SC	Supply Chain

SD	System Dynamics
SP	Steel Plant
SMM	Sustainable Manufacturing Mapping
SSC	Sustainable Supply Chains
ST	Simulation techniques-Digital twin
TQM	Total Quality Management
VNM	Value Network Mapping
VSM	Value Stream Mapping

Appendix

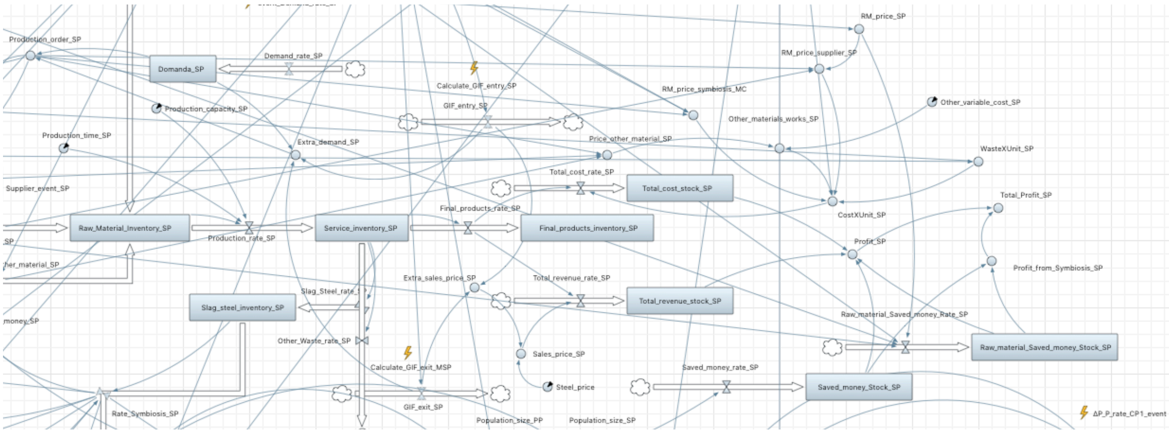

Figure 54: SD model of the Steel plant

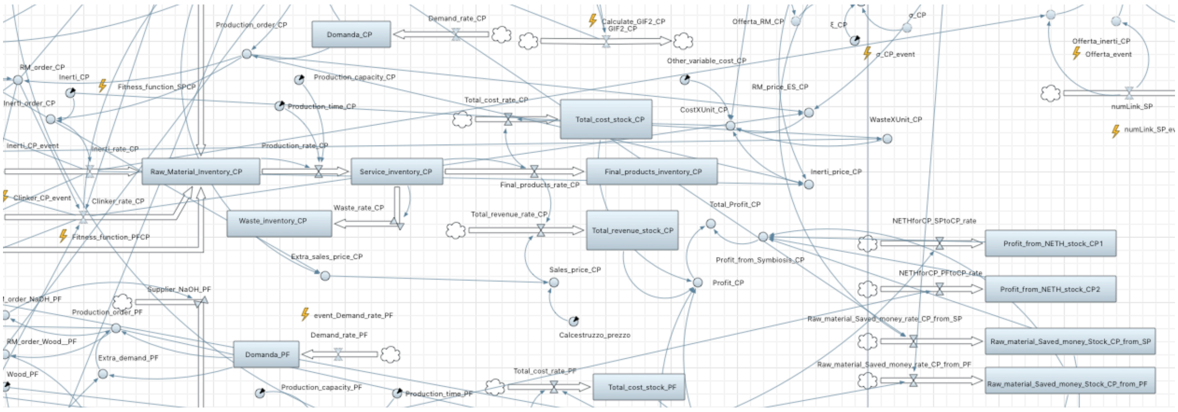

Figure 55: SD model of the Cement plant

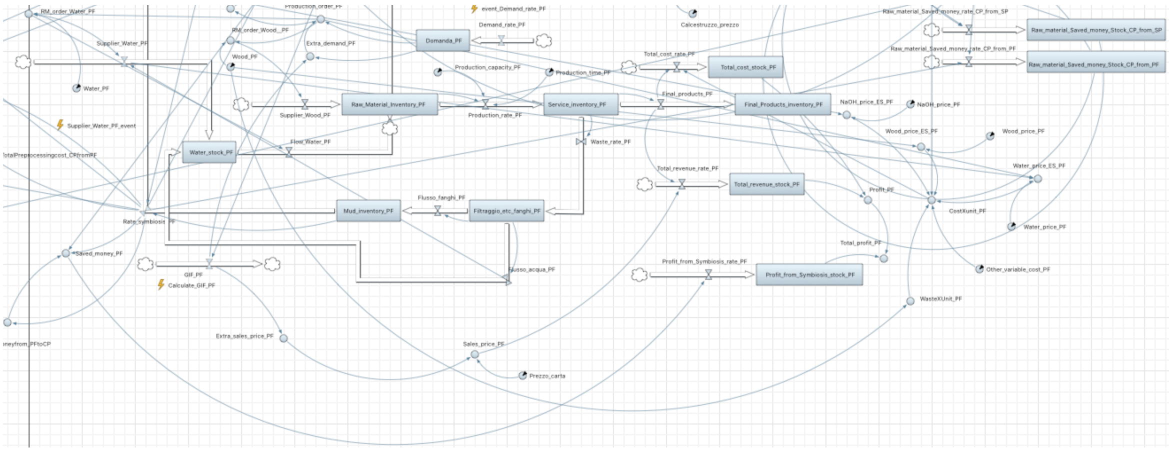
Figure 56: SD model of the Paper factory

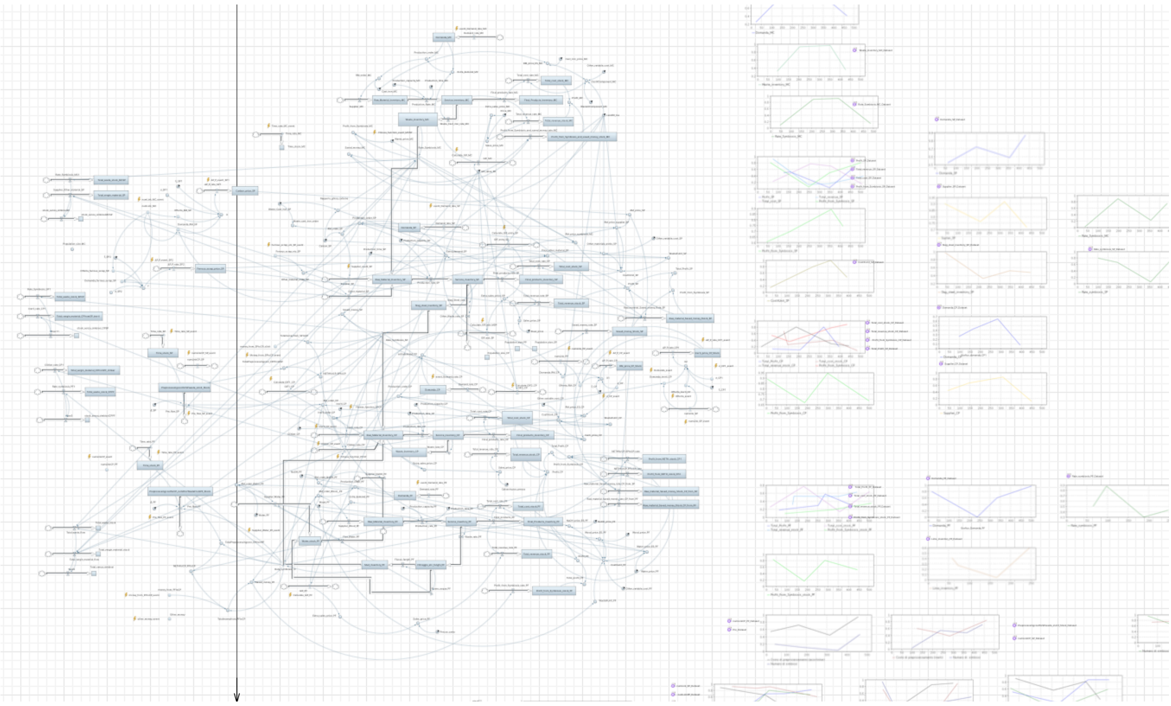

Figure 57: Complete model

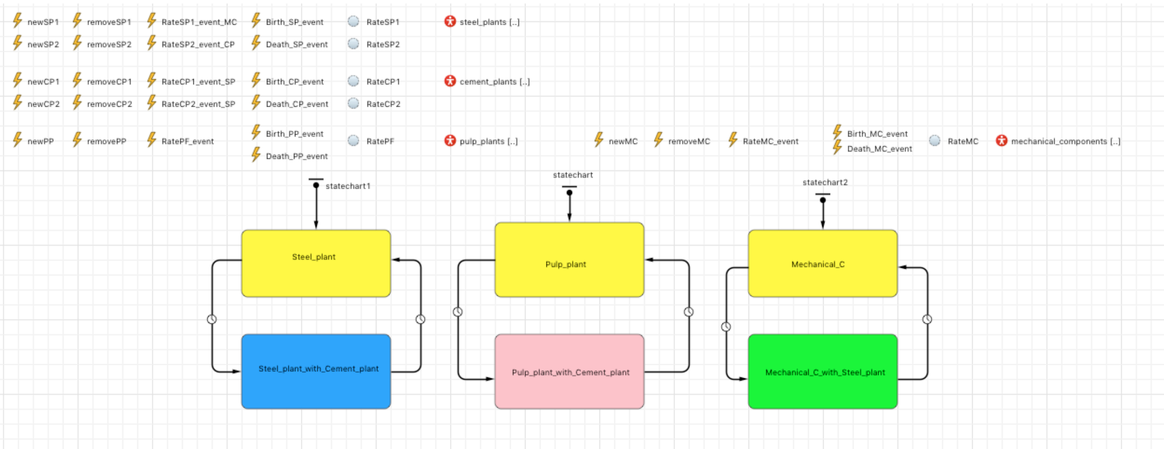

Figure 58: State chart of the companies